# The Carbon Isotopes of the First Stars.

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Ryan Cooke, Michele Fumagalli, and Max Pettini

Caltech Tea Talk 22$^{nd}$ June 2020

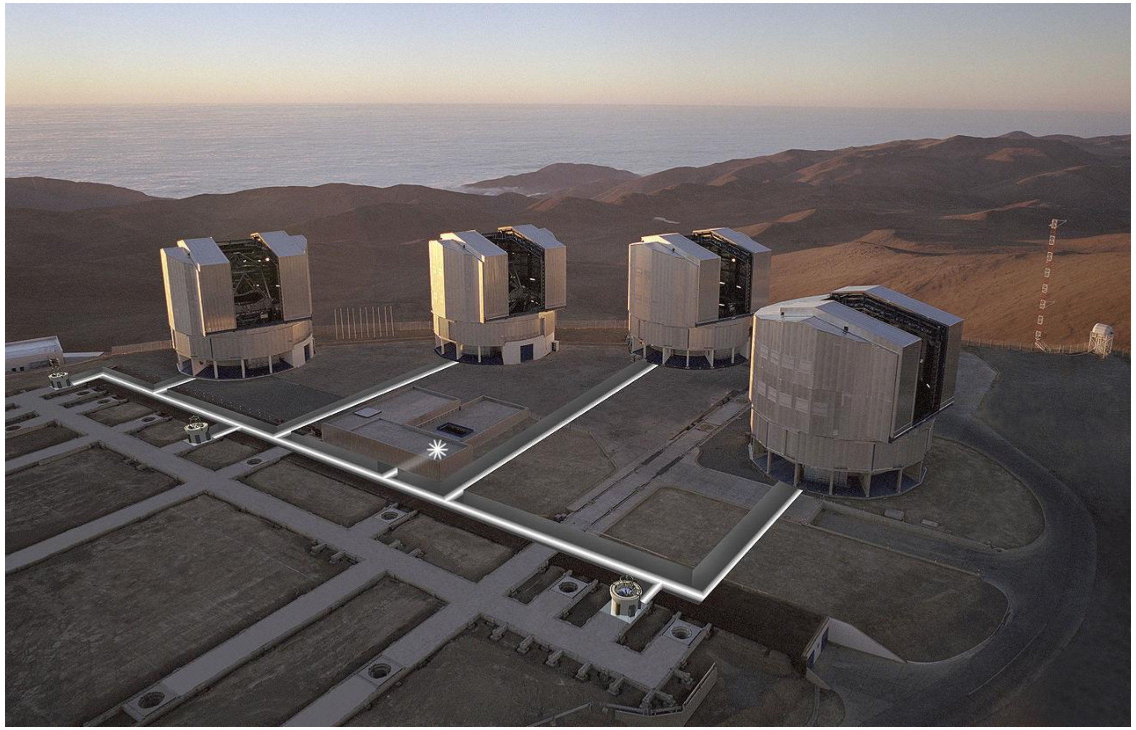


Image credit: ESO

Durham Centre for Extragalactic Astronomy

Durham University

# Population III stars

- First generation of stars to form in the Universe,
- Thought to have formed between a redshift of $z \sim 20 - 30$,
- Necessarily formed from metal-free environment.

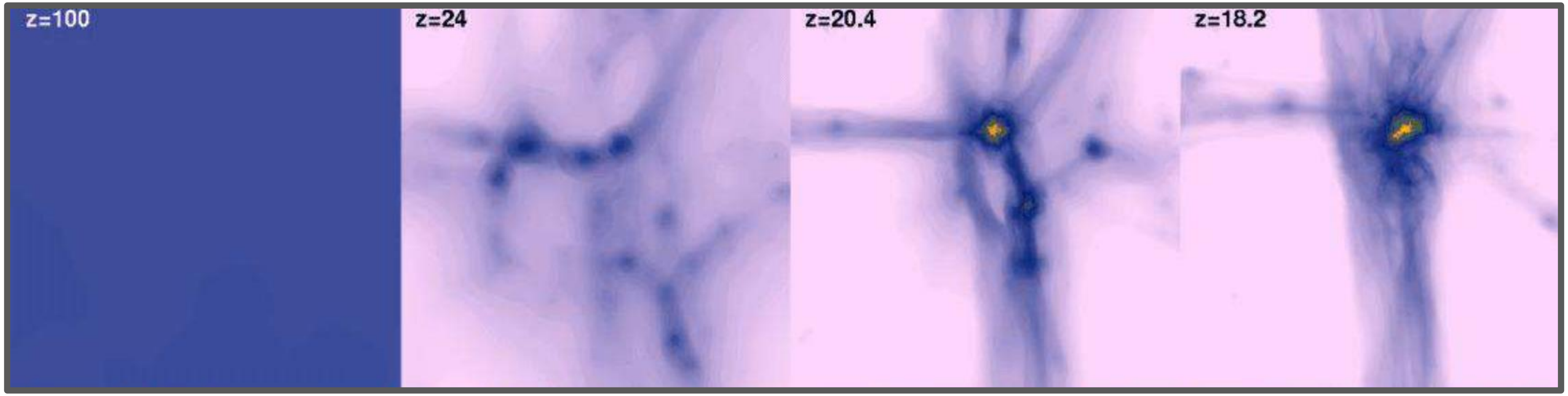


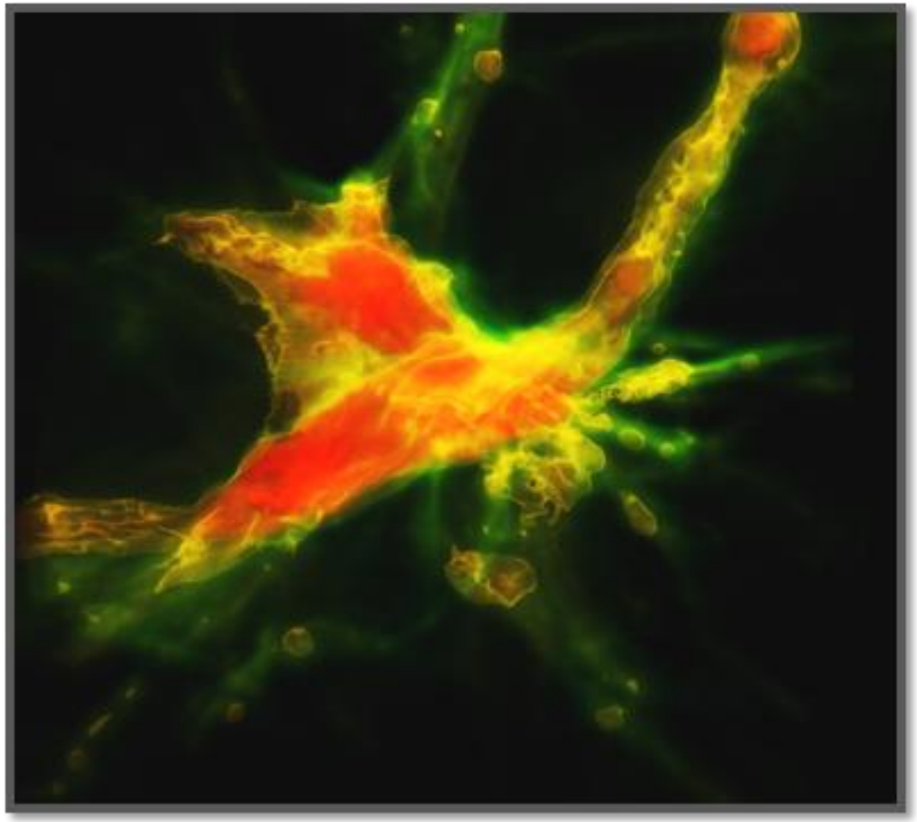
Image credit: Abel, Bryan, and Norman (2001)

# Population III stars

- Thought to have formed with higher masses than stars forming from metal-enriched gas,

- Current typical mass range from simulations ~ 10 - 100 $M_{\odot}$,

- Some simulations suggest formation of low-mass (~1$M_{\odot}$) stars is possible (e.g. Clark et al. 2011, Stacy & Bromm 2014, Stacy et al. 2016).



Greif et al. (2008)

# Population III stars

- We are yet to detect a metal-free star despite dedicated surveys spanning ~ 4 decades (Bond 1980 – Da Costa 2019),
- Can search for surviving chemical signature in potential Population III relics.

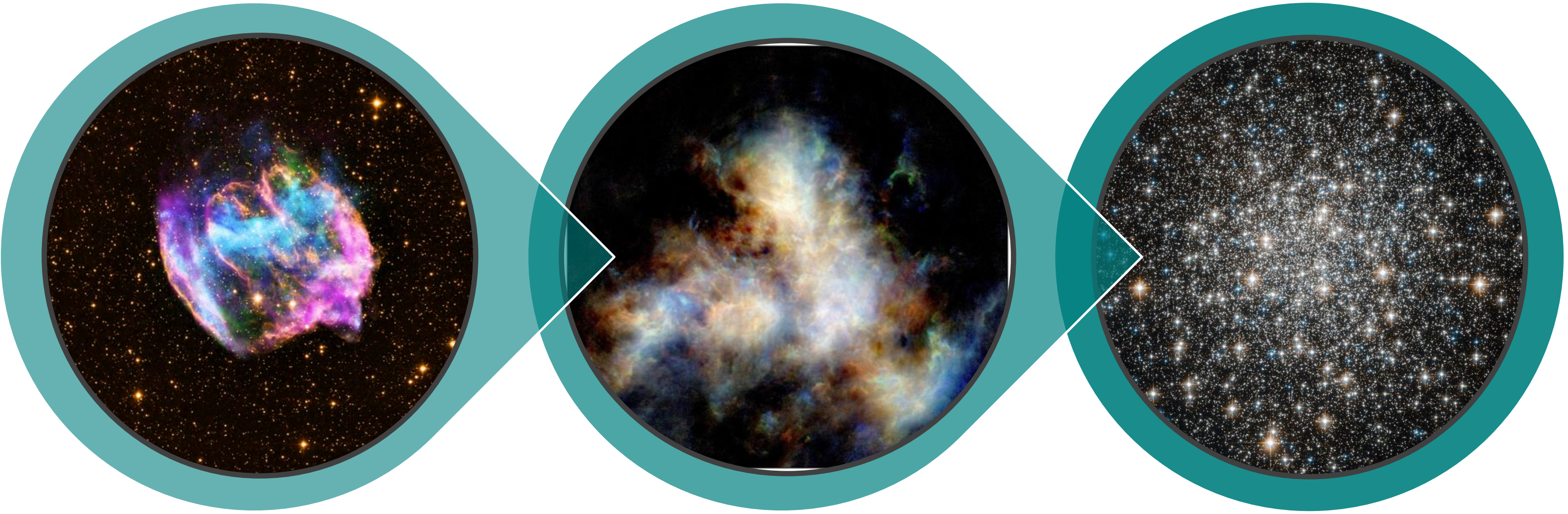
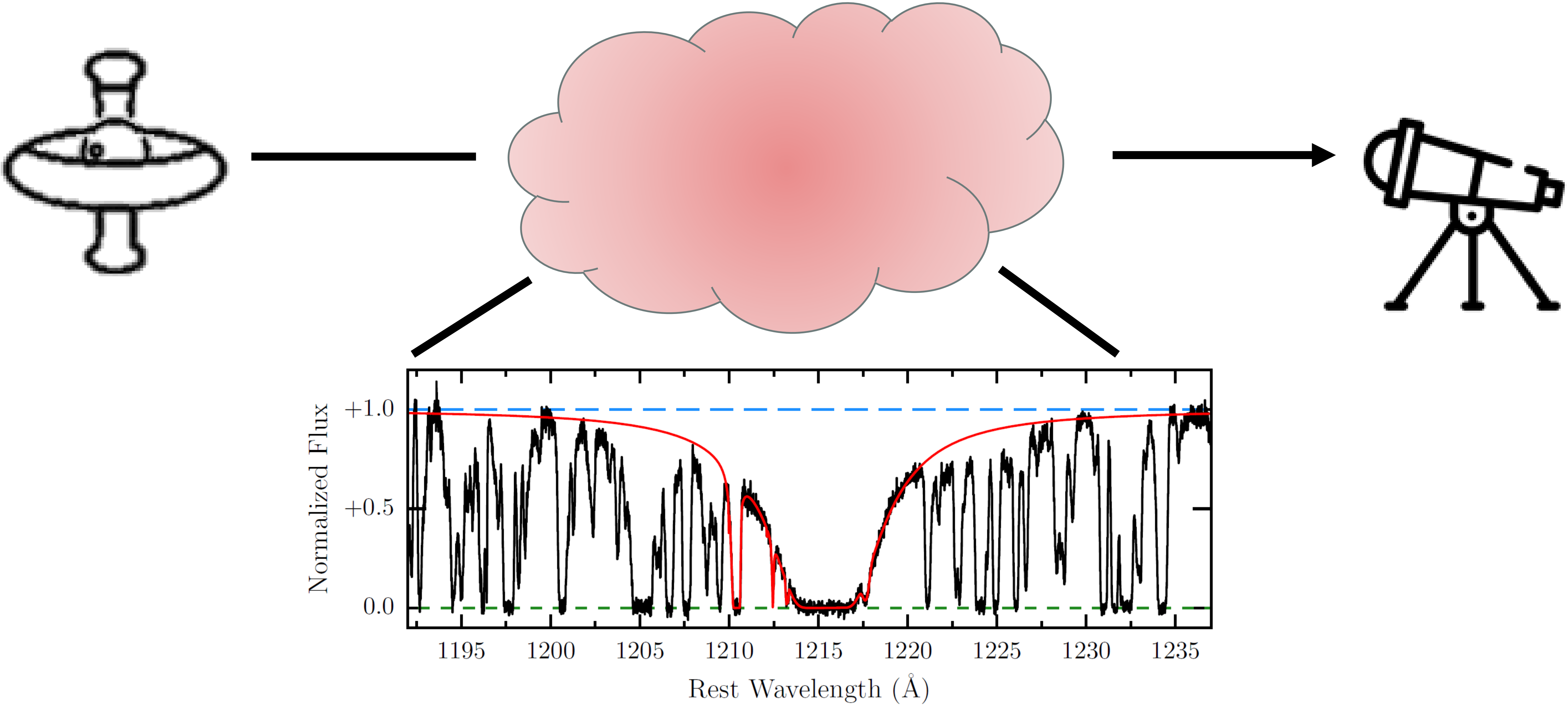


Image credit: X-ray: NASA/CXC/MIT/L.Lopez et al.; Infrared: Palomar; Radio: NSF/NRAO/VLA

Image credit: Naomi McClure-Griffiths et al., CSIRO's ASKAP telescope

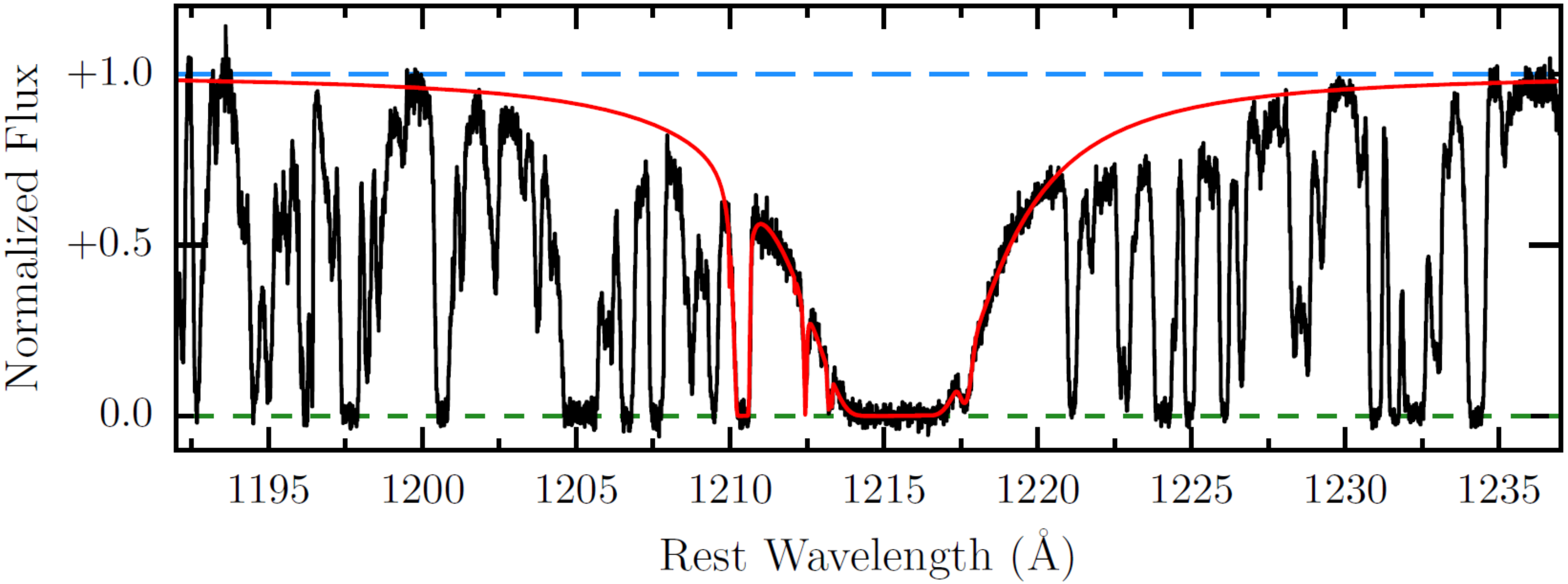
Image credit: ESA/NASA

# Damped Lyman Alpha systems (DLAs)

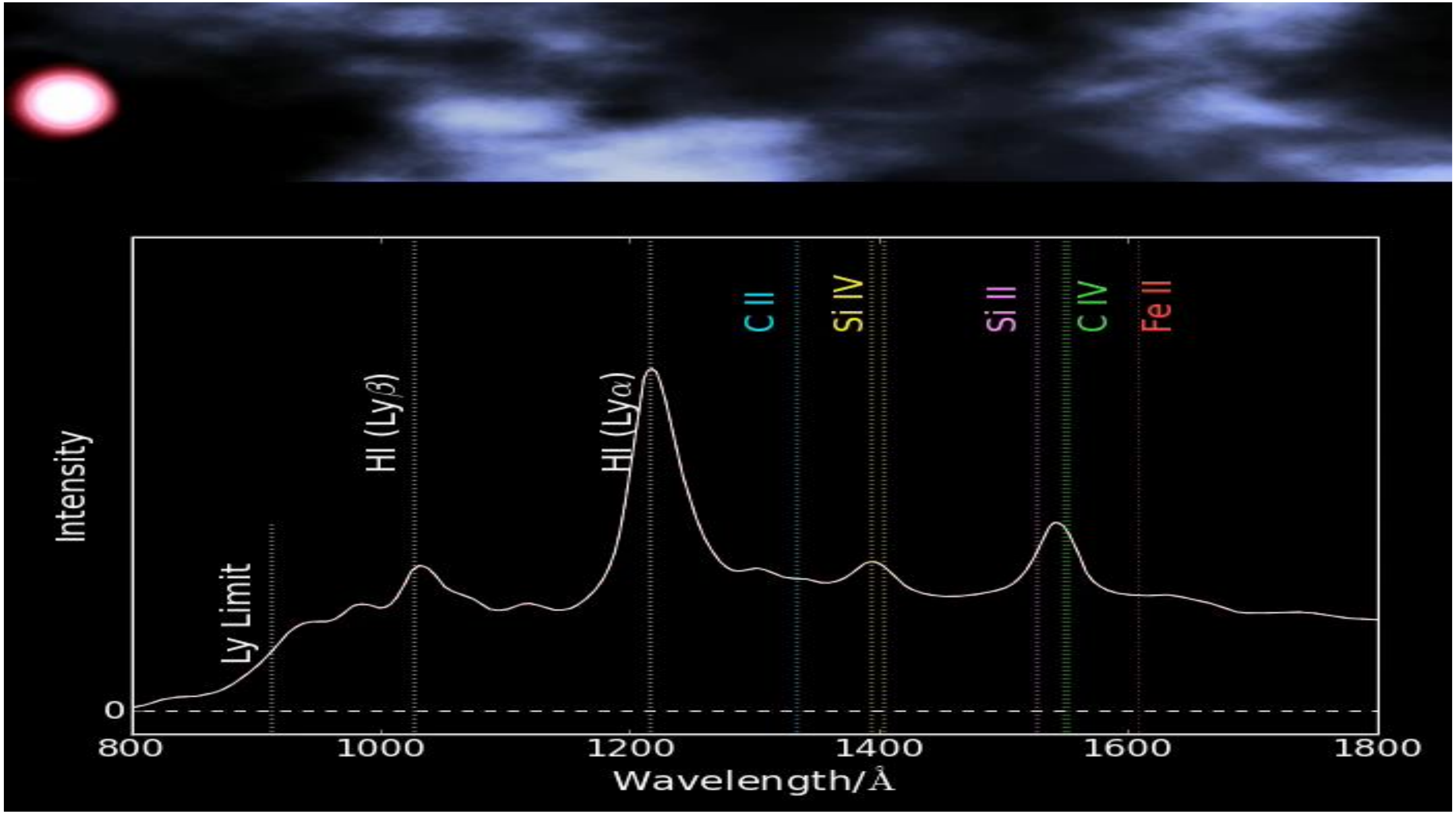


# Damped Lyman Alpha systems (DLAs)

- Clouds of mostly neutral hydrogen found along the line-of-sight towards unrelated background quasars,
- Easy to identify in spectra from their strong damping wings,
- Characterised by a H I column density N(H I) $\geq 10^{20.3}$cm$^{-2}$ .



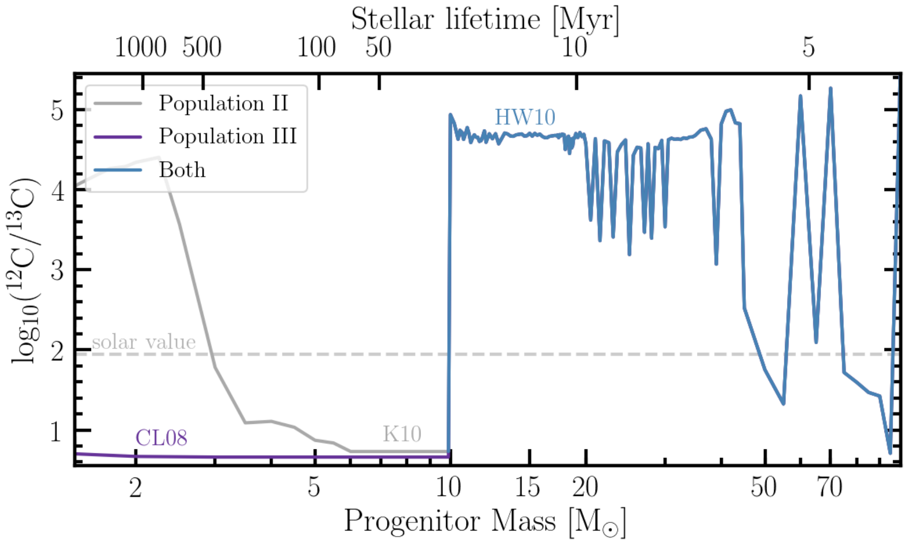
# Damped Lyman Alpha systems (DLAs)



# Carbon Isotope Ratio

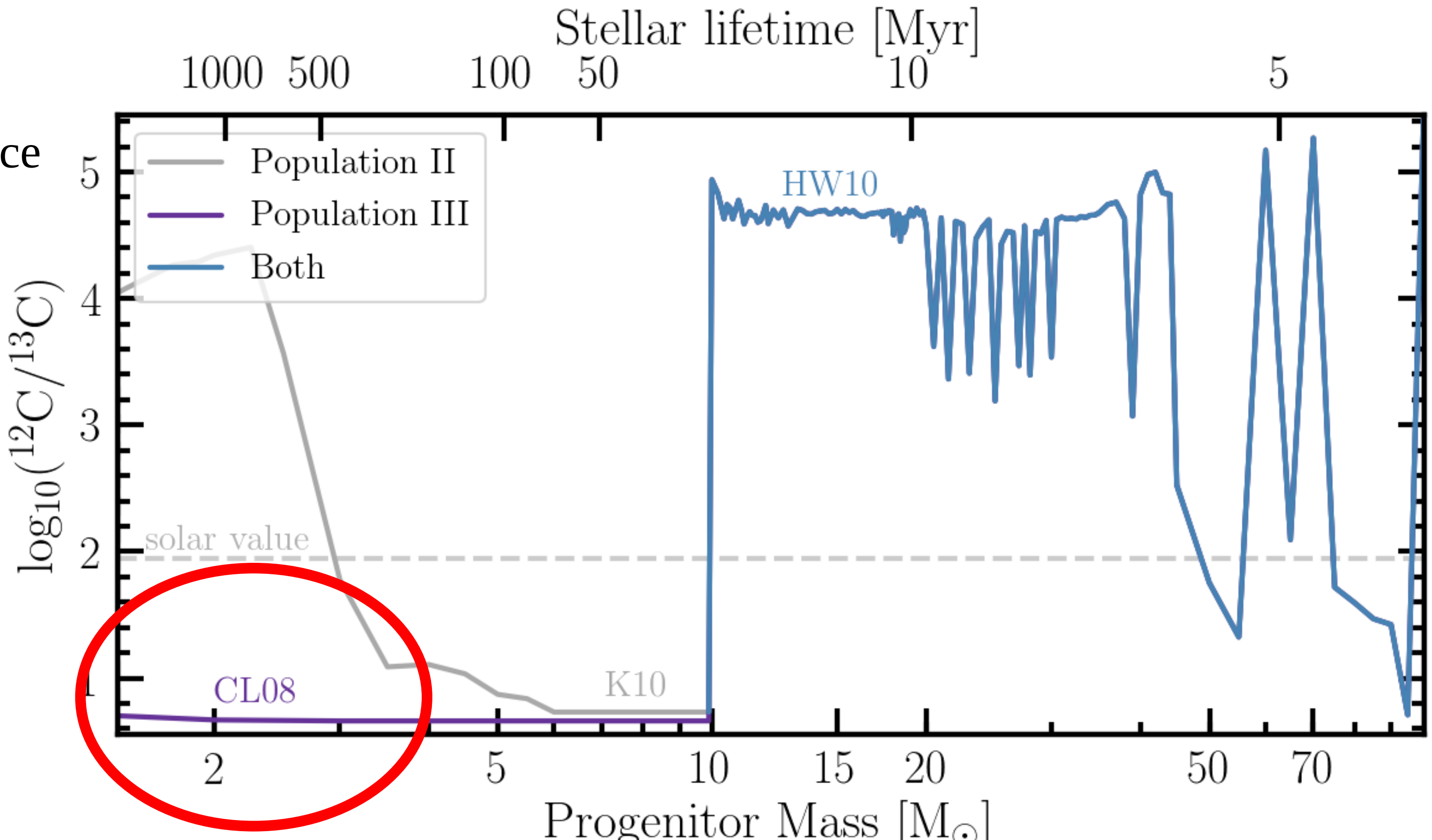
- Simulations of stellar evolution suggest most stars predominantly produce $^{12}$C,

- There are two channels to produce low $^{12}$C/$^{13}$C ratios in non-rotating stars:
    → Low-mass Population III stars
    → Intermediate-mass Population II stars



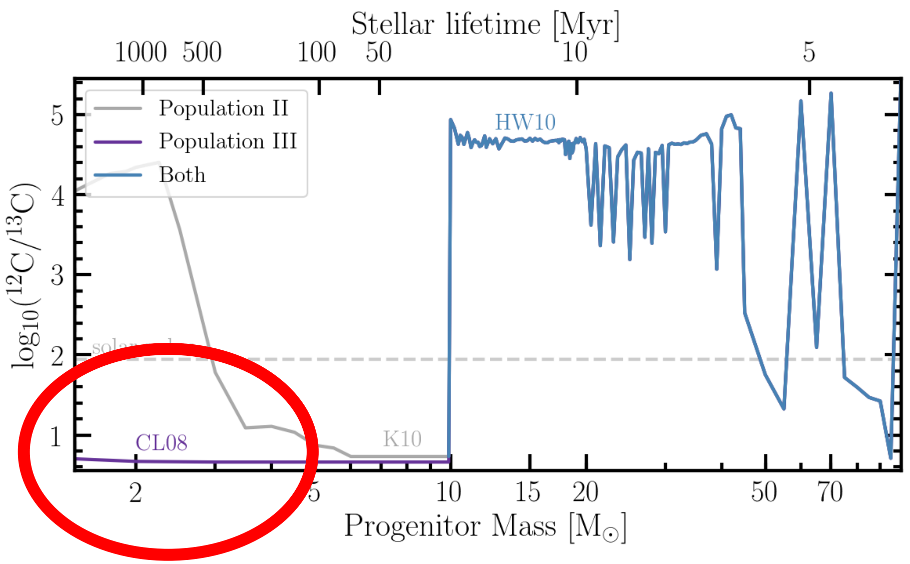
# Population III Yields

Number abundance ratio

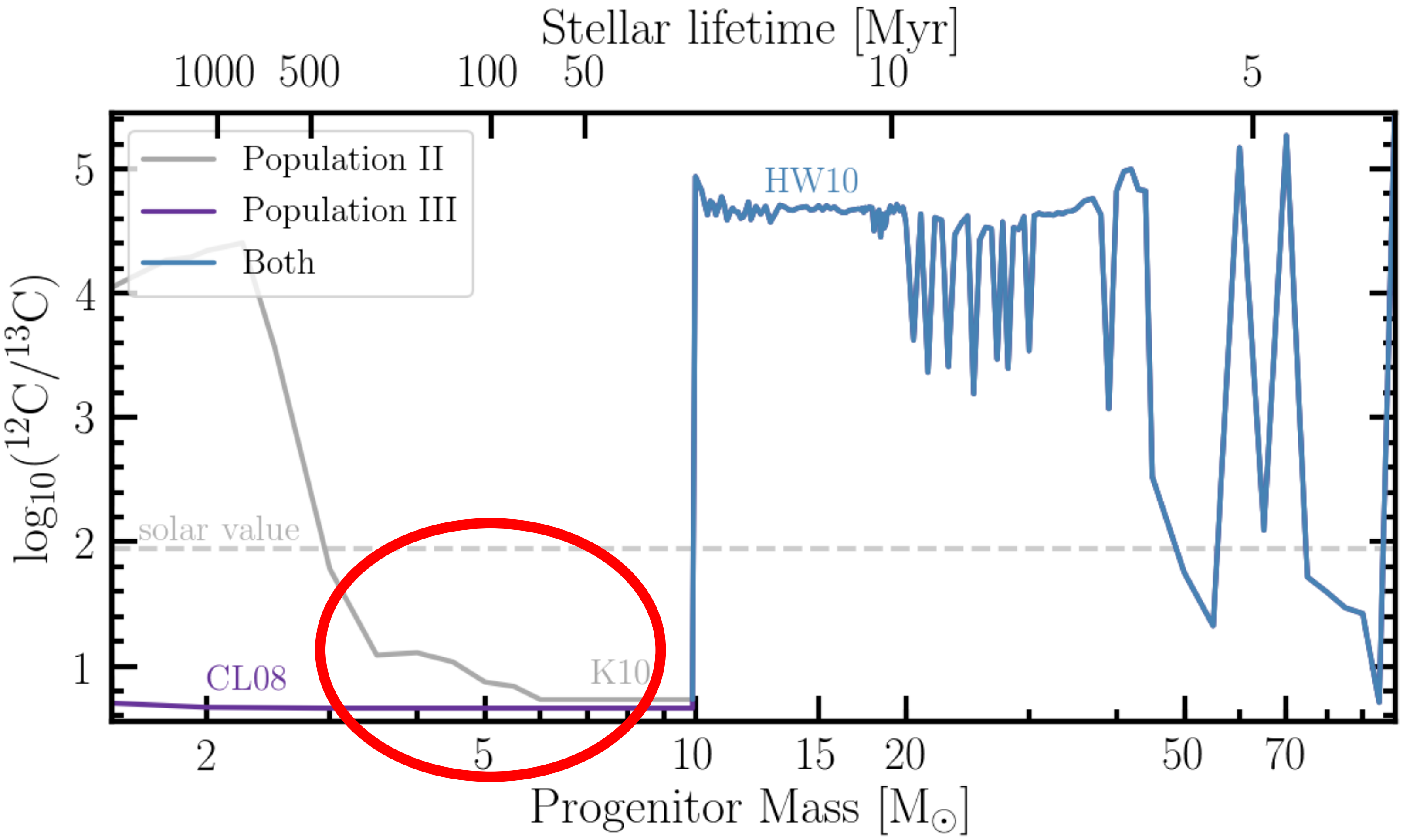


# Population III Yields

- Long-lived, low-mass Population III stars enrich environment through mass loss,
- Unique "violent" nucleosynthetic episodes followed by He burning (Kobayashi 2011),
- Campbell & Lattanzio (2008) simulations suggest low-mass Population III stars produce $^{12}C/^{13}C < 6$.

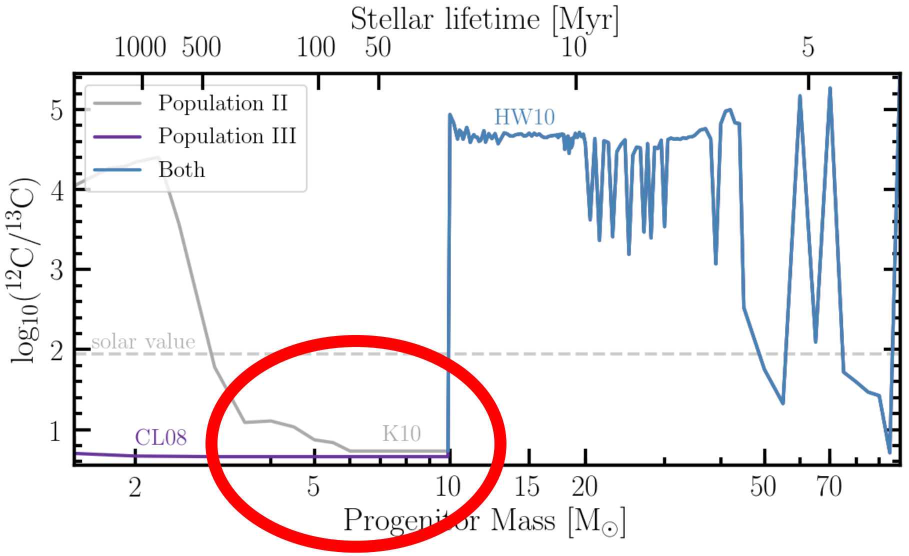


# Population II Yields

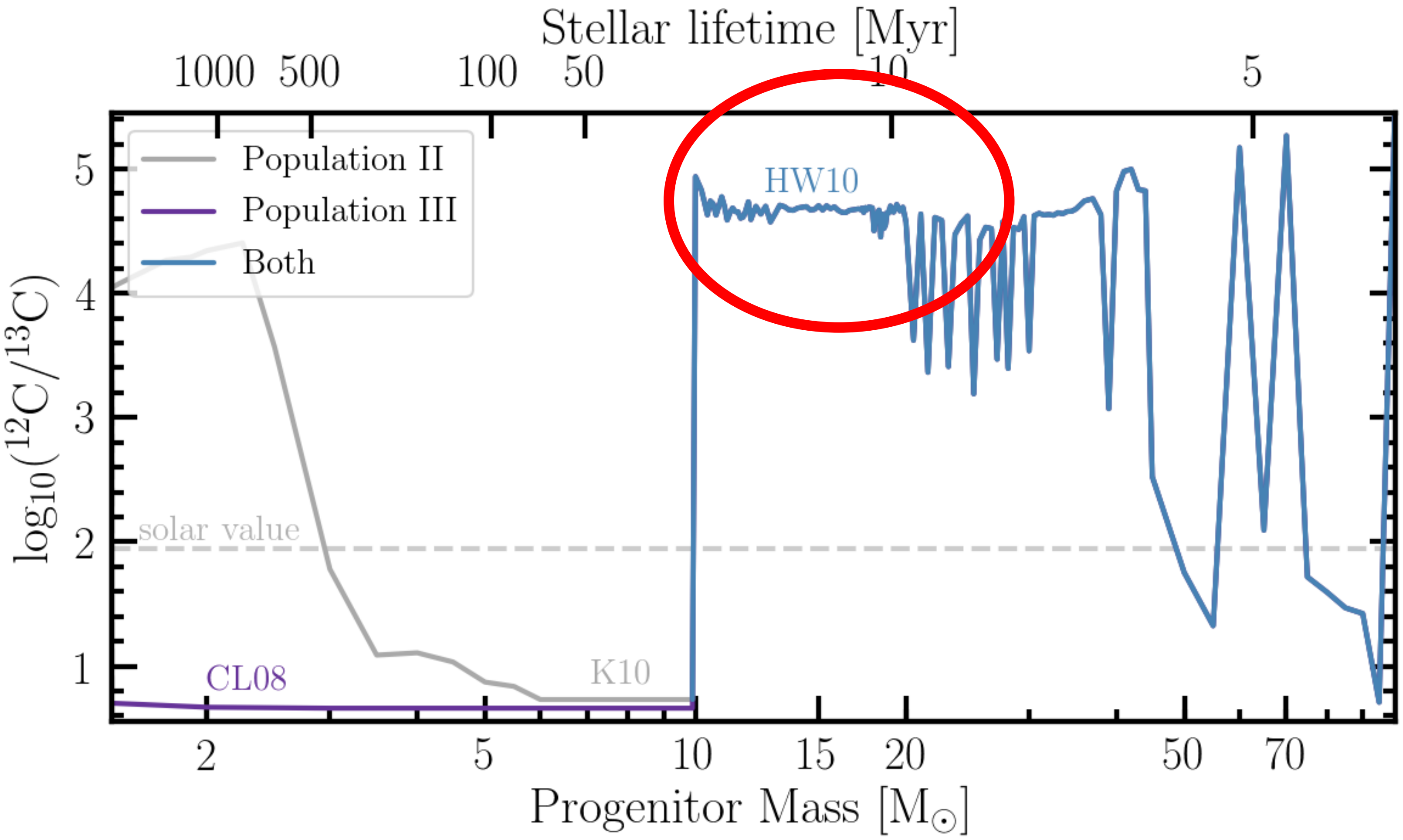


# Population II Yields

- Population II AGB stars enrich environment through mass loss,
- Convective envelope during Hot Bottom Burning transports $^{12}C$ to proton-rich areas leading to $^{13}C$ production (Iben 1975; Prantzos et al. 1996; Kobayashi et al. 2011),
- Karakas (2010) suggests Population II AGB stars in the mass range 4 - 6 $M_\odot$ produce $4 < {}^{12}C/{}^{13}C < 12$.

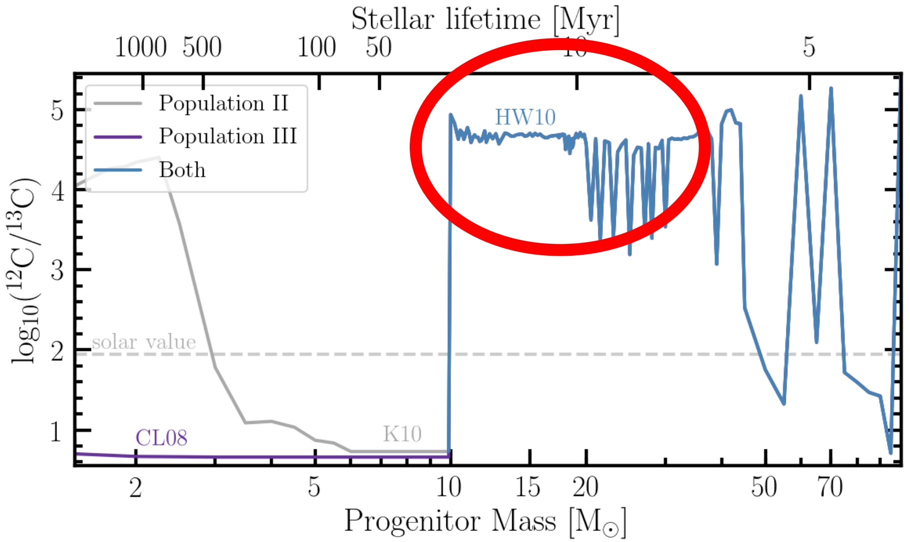


# Both Yields


Stellar lifetime [Myr]
1000
500
100
50
10
5
Population II
Population III
Both
HW10
solar value
CL08
K10
$\log_{10}(^{12}C/^{13}C)$
5
4
3
2
1
2
5
10
15
20
50
70
Progenitor Mass [$M_\odot$]

# Both Yields

- Short-lived, massive stars enrich environment through core-collapse supernovae,
- Surface mixing events not seen above $10M_\odot$ (Karakas & Lattanzio 2014). $^{13}C$ is only produced through secondary processes regardless of metallicity,
- Heger & Woosley (2010) simulations suggest $^{12}C/^{13}C > 1000$.

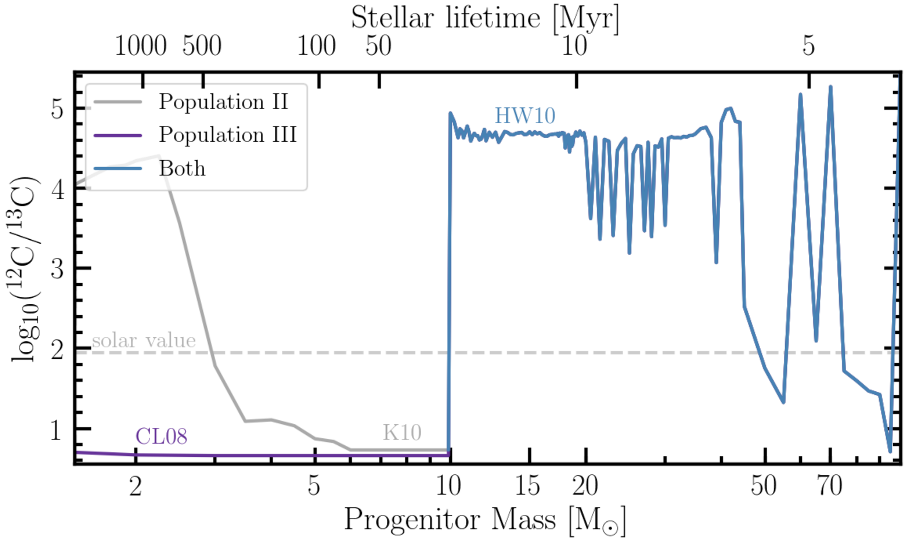


# Carbon Isotope Ratio

- Measuring the $^{12}C/^{13}C$ ratio in a near-pristine system will therefore show:

→ Whether low-mass Population III stars have contributed to enrichment,

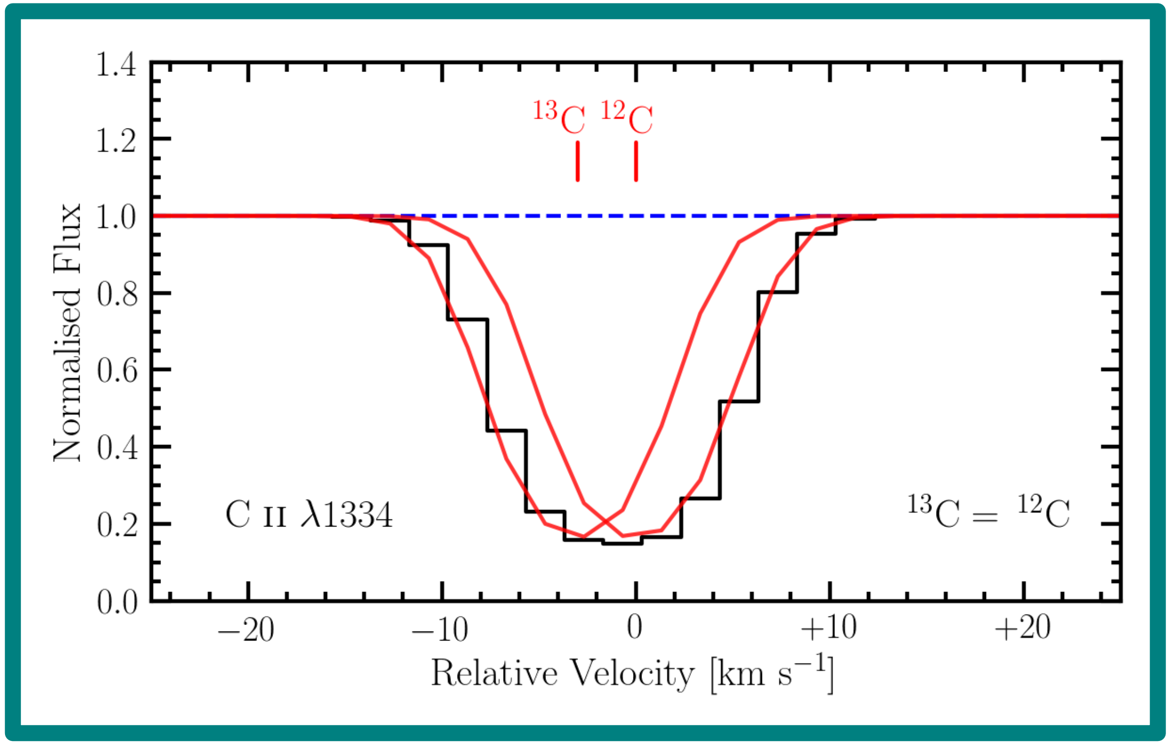
→ The timescale on which the system has been enriched.

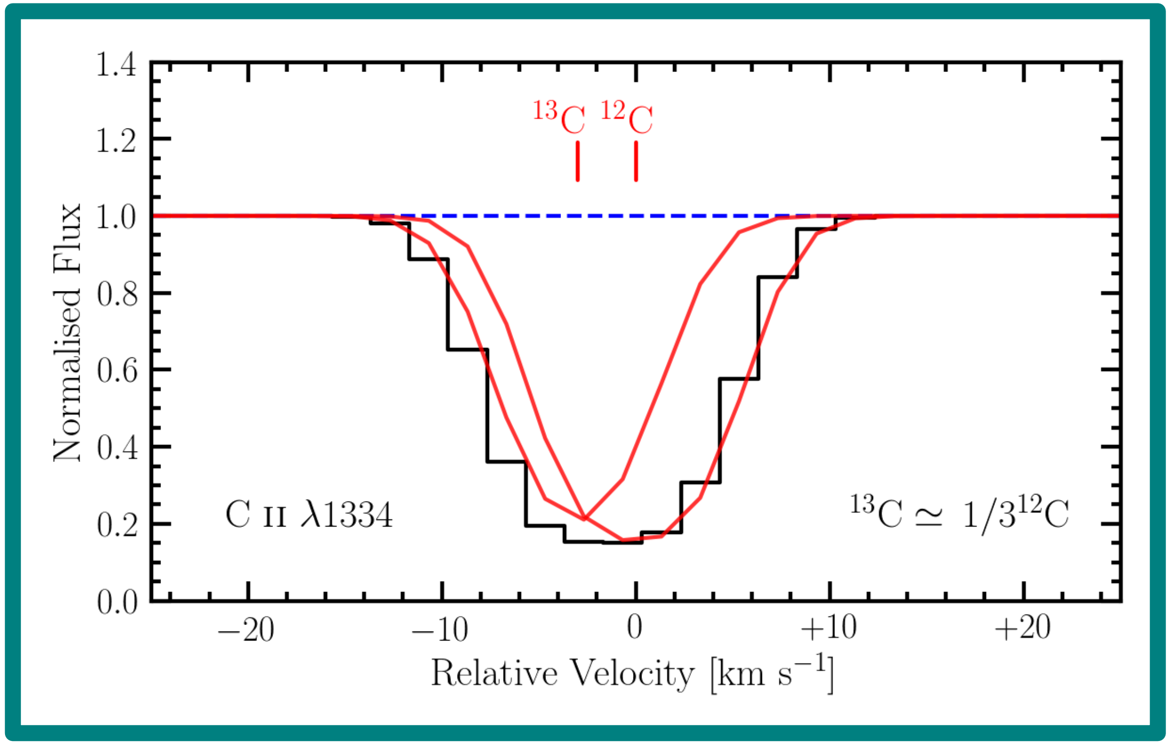


# The struggle…

# C II λ1334

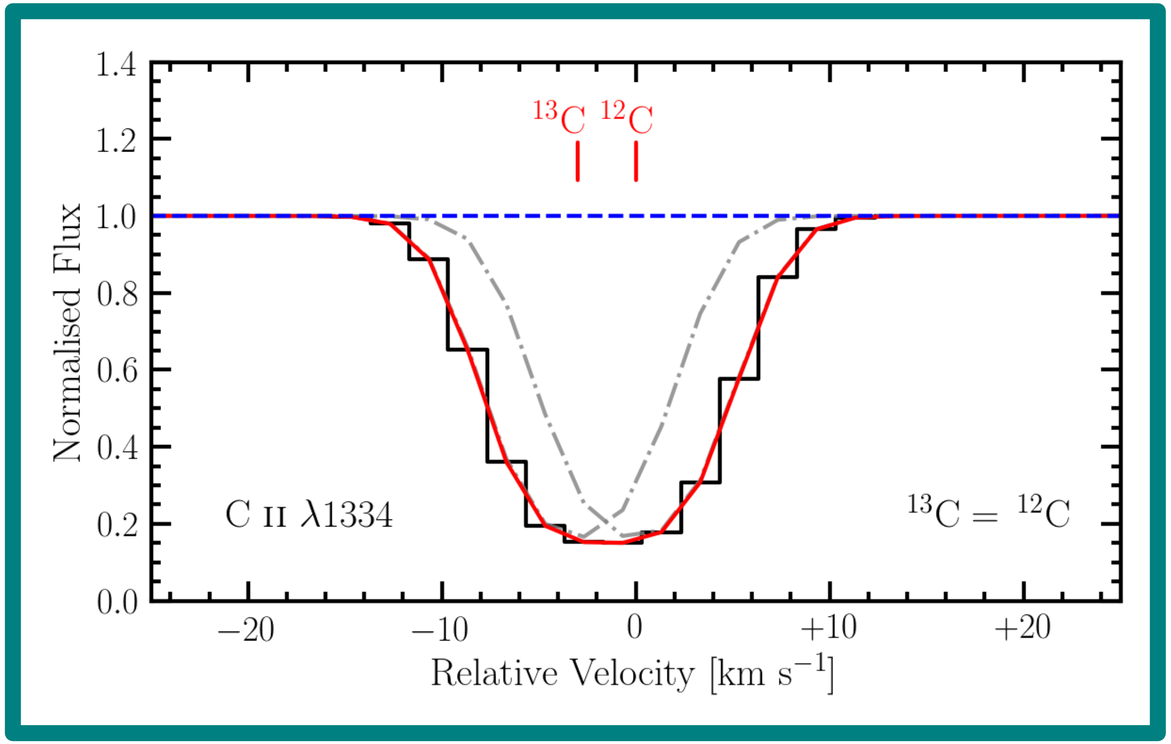
The C II λ1334 isotope lines are separated by 2.99 km s$^{-1}$

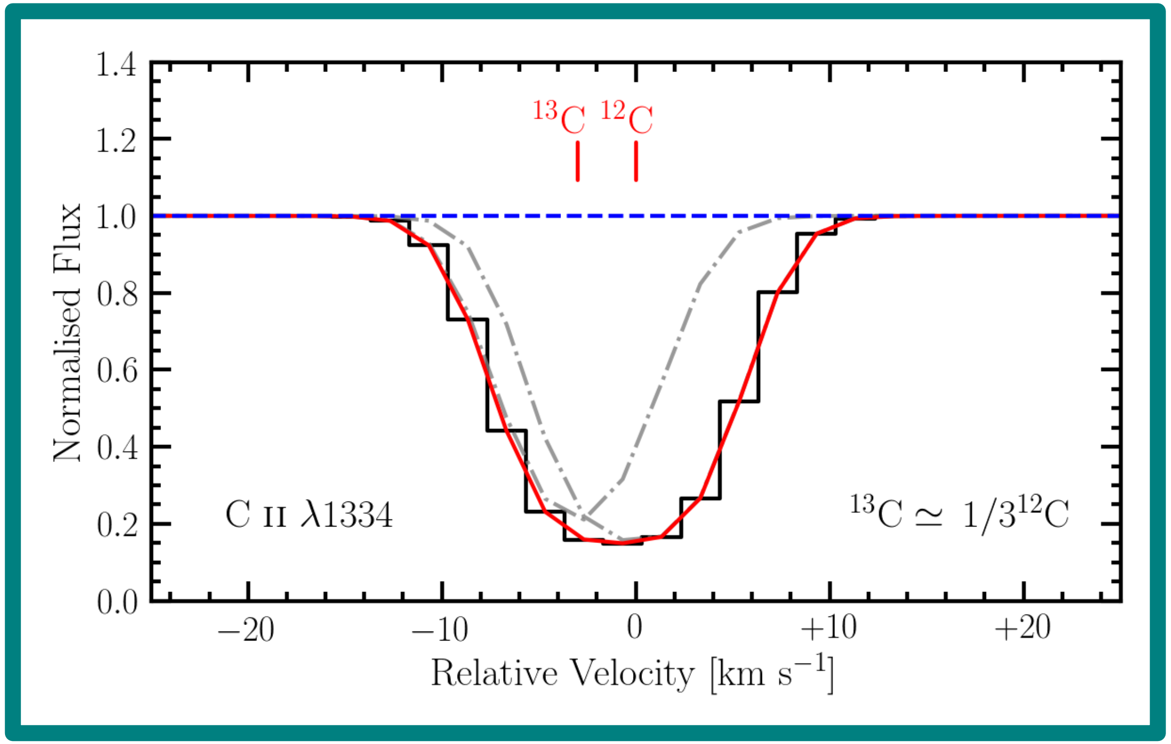




# C II λ1334

The presence of $^{13}$C is seen as an asymmetry in C II λ1334 line





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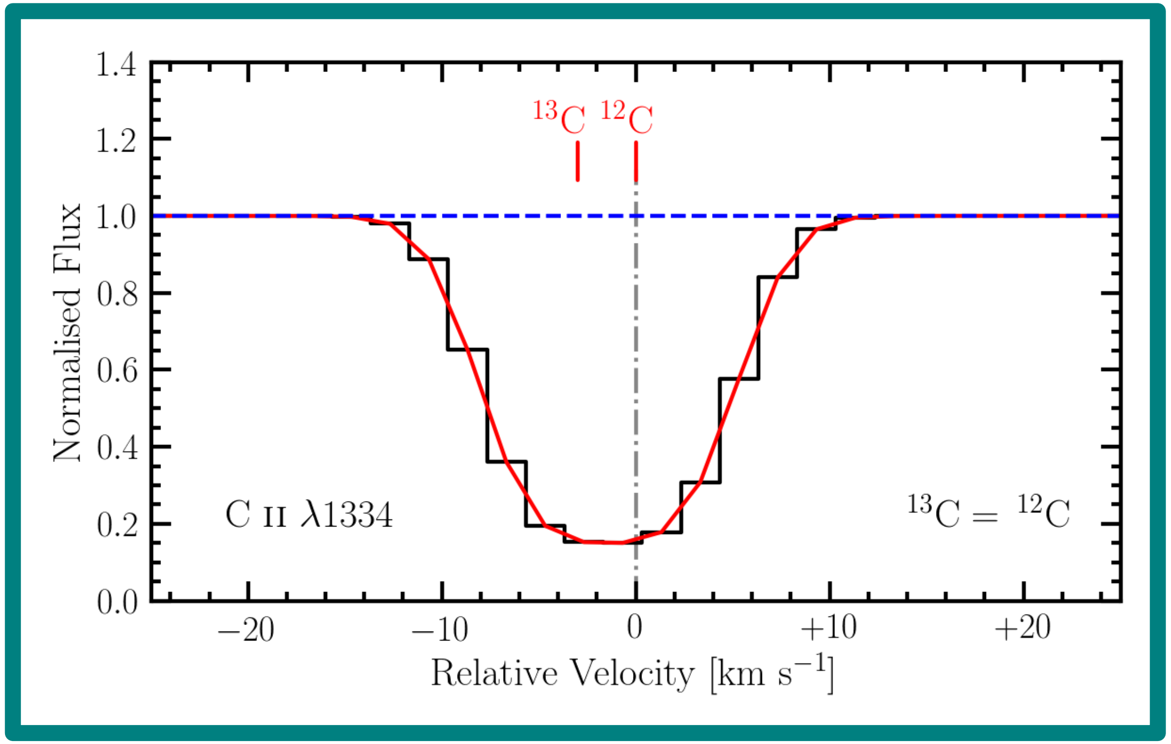

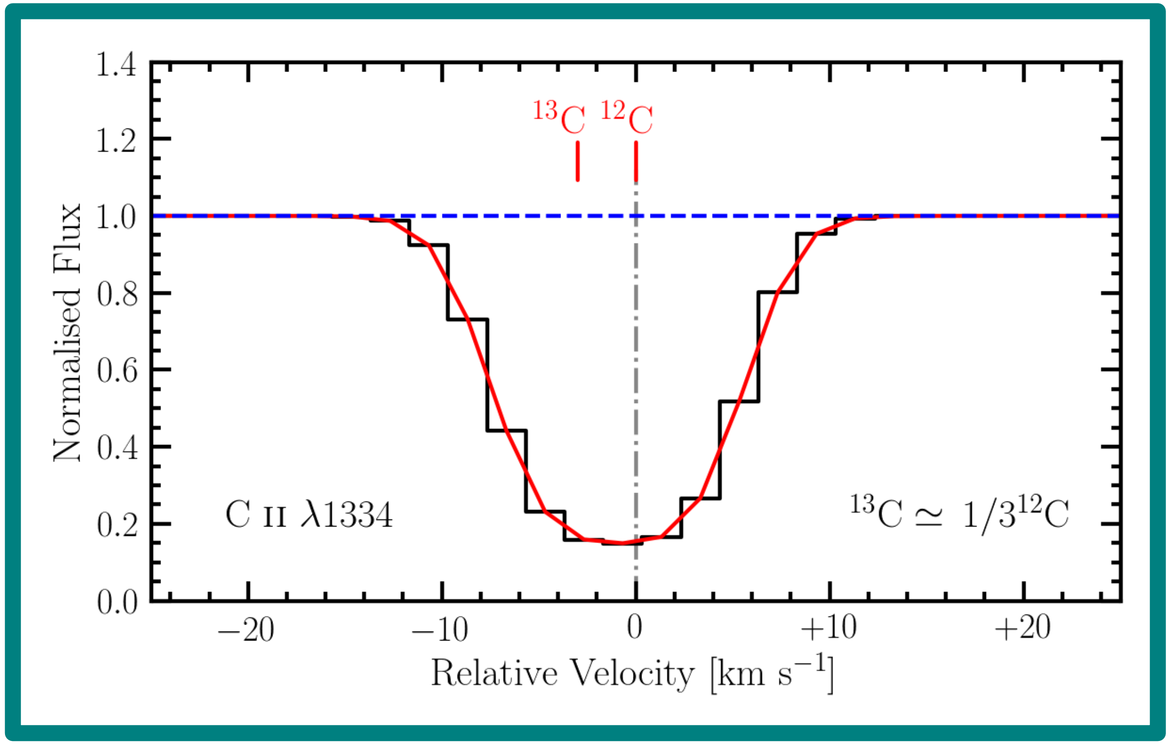

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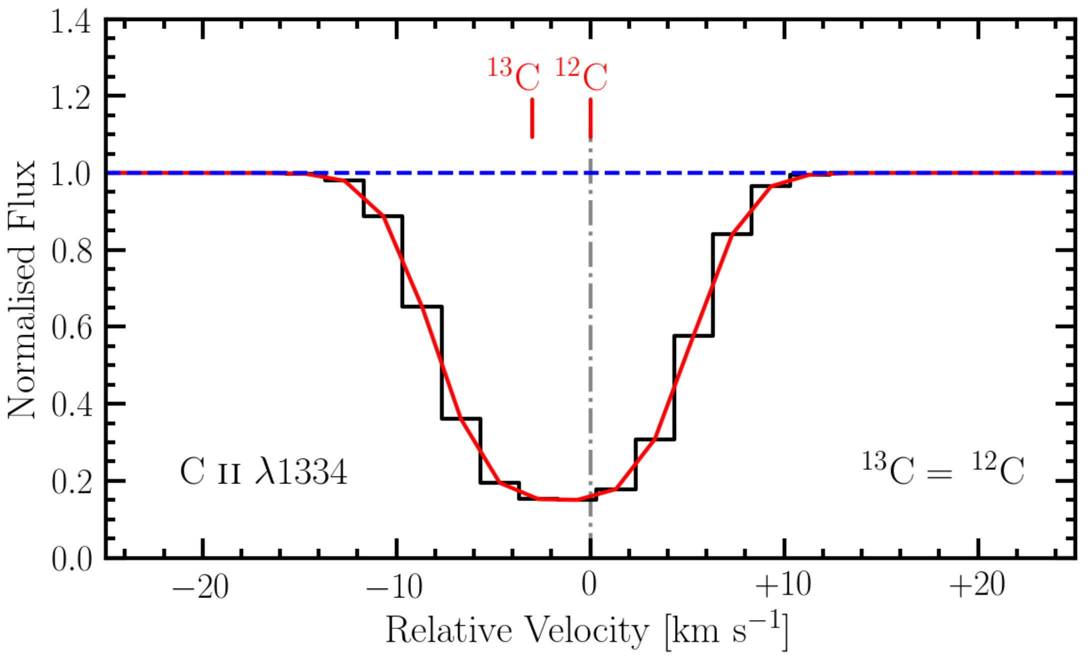
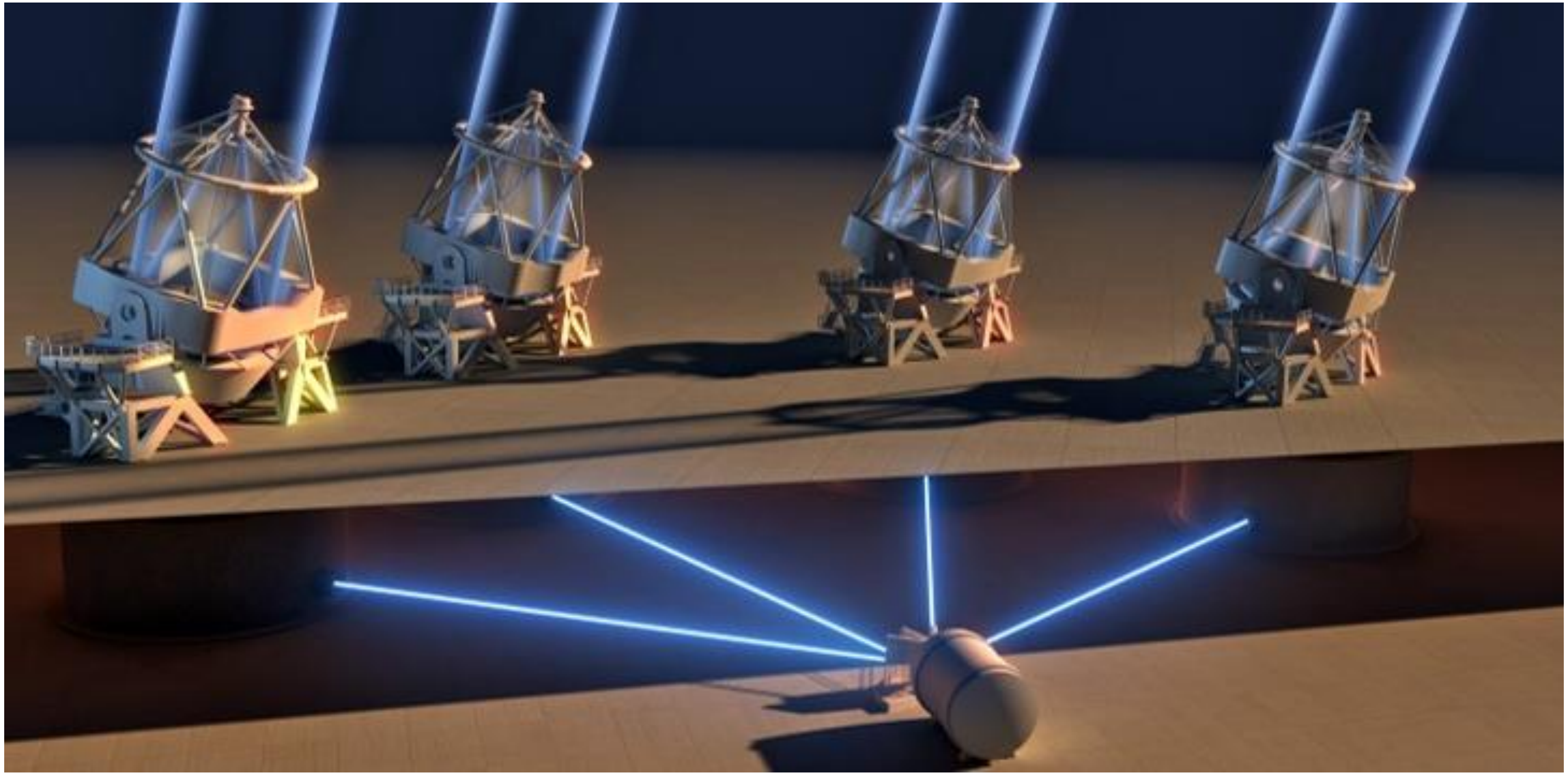


If the line centre of $^{12}$C can be determined from other absorption lines then we can detect the asymmetry.

This requires an accurate wavelength solution.

# A measurement requires:

# 1. ESPRESSO (The Echelle SPectrograph for Rocky Exoplanets and Stable Spectroscopic Observations)



# 1. ESPRESSO (The Echelle SPectrograph for Rocky Exoplanets and Stable Spectroscopic Observations)

- Ultra-stable spectrograph,
- Unprecedented wavelength accuracy,
- Relative velocity accuracy better than 5m $s^{-1}$, wavelength accuracy of ~$10^{-4}$ Å at 4000Å,
- Resolution in 4UT mode is 70,000.

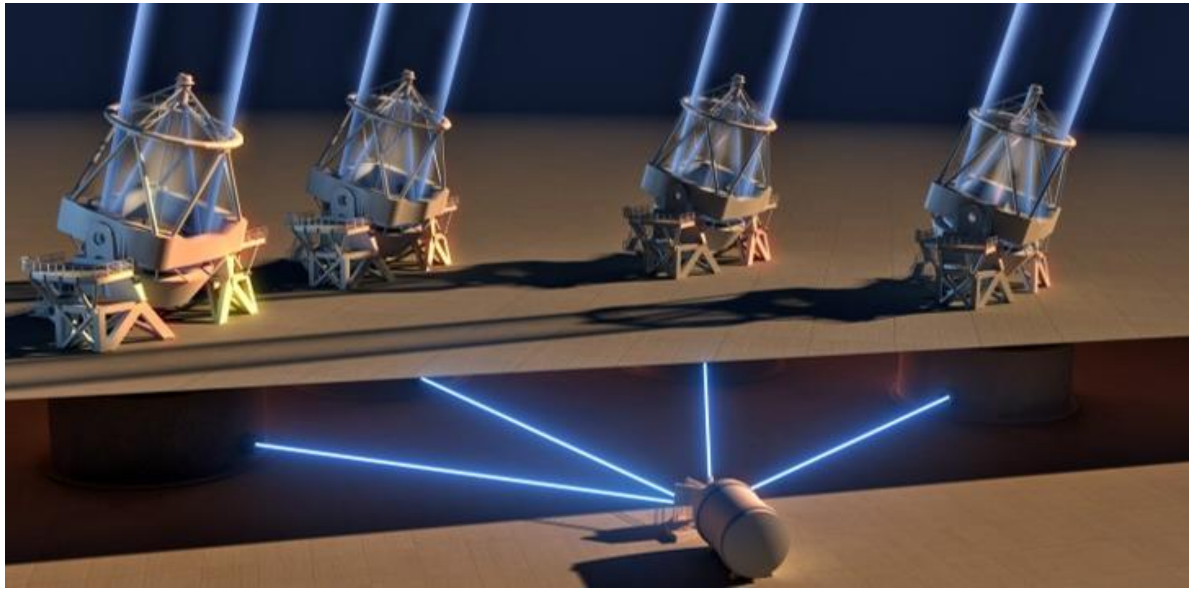
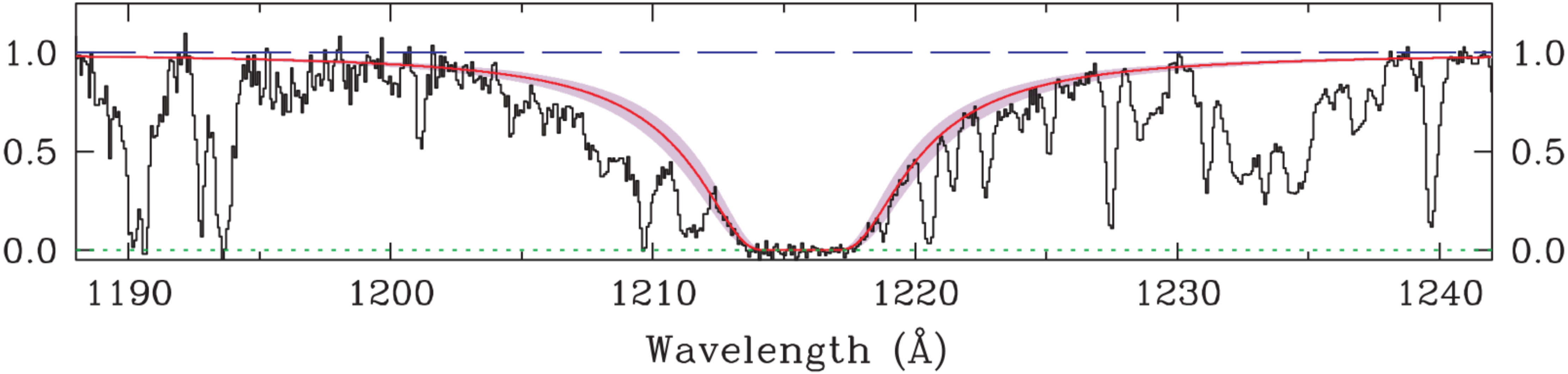


Image Credit: ESO

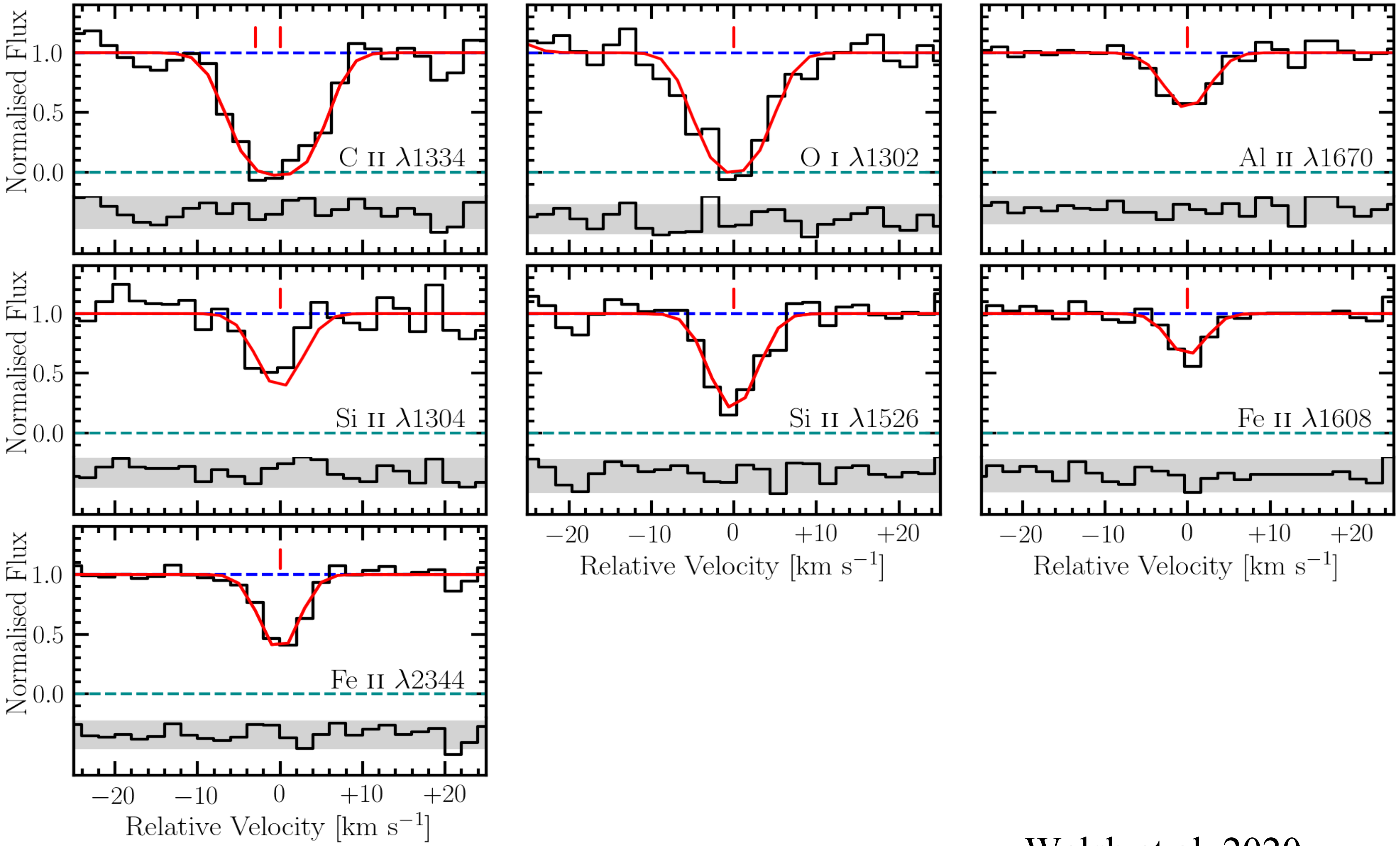
# 2. A Promising DLA

- Found at $z_{abs}$~ 2.340 along the line-of-sight towards quasar J0035-0918
- Large neutral hydrogen column density $\log_{10}$ N(HI)/cm$^{-2}$ = 20.43 ± 0.04
- [Fe/H] = -2.94 ± 0.06 where $[X/Y] = \log_{10}(N_X/N_Y) - \log_{10}(N_X/N_Y)_\odot$
- Total Doppler parameter ~ 3.5 km s$^{-1}$

Cooke et al. (2011)



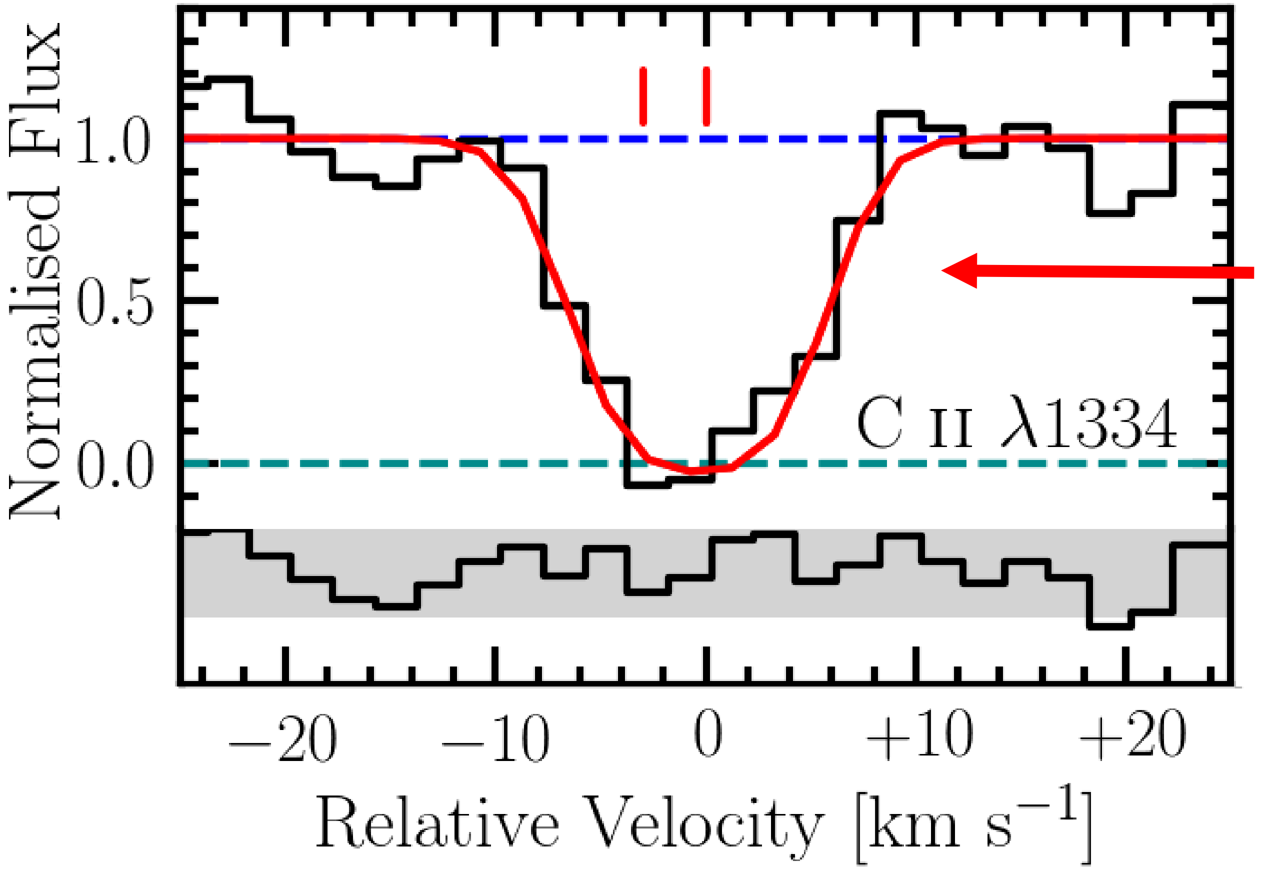
# The Data



Welsh et al. 2020

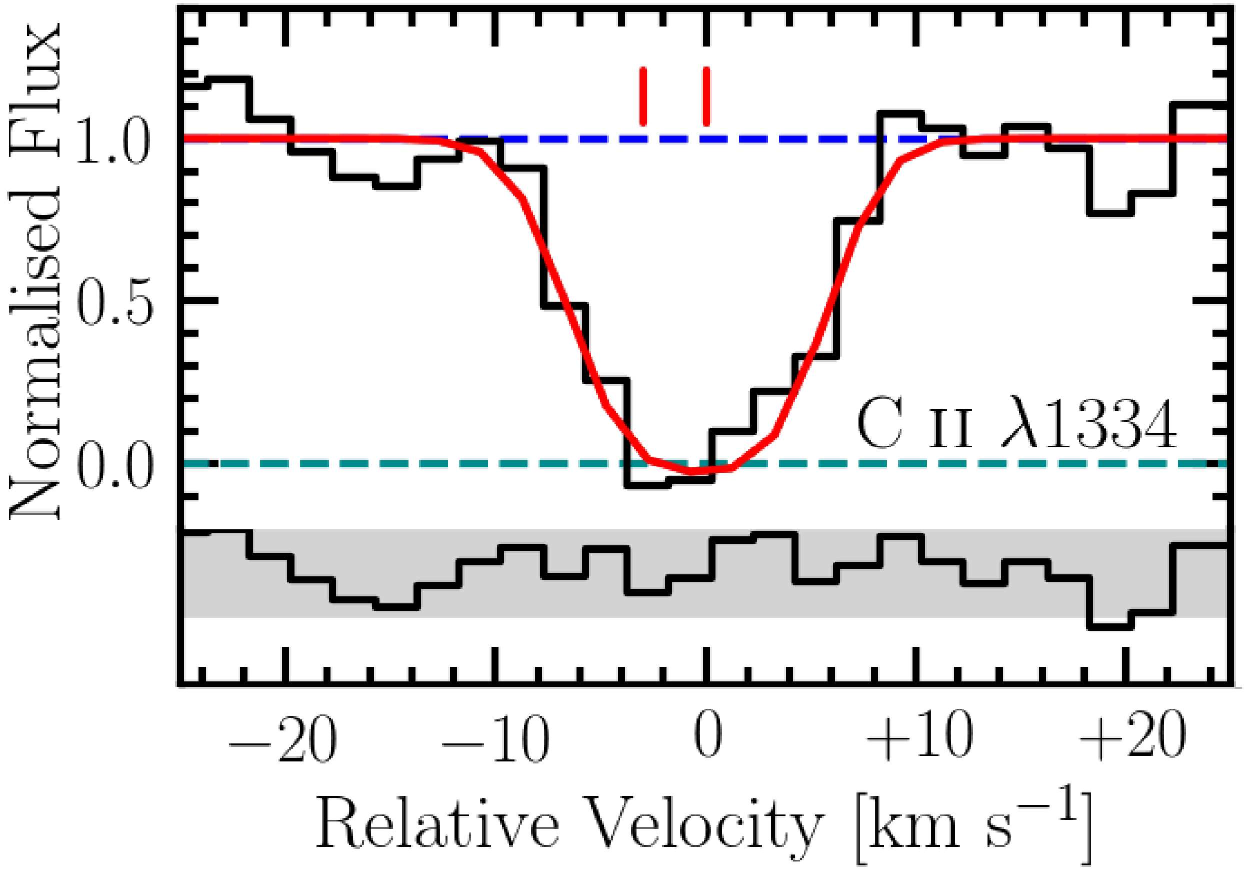
# Best Fit Profile

Welsh et al. 2020



$\log_{10}{}^{12}C/{}^{13}C = 1.15$

# Best Fit Profile



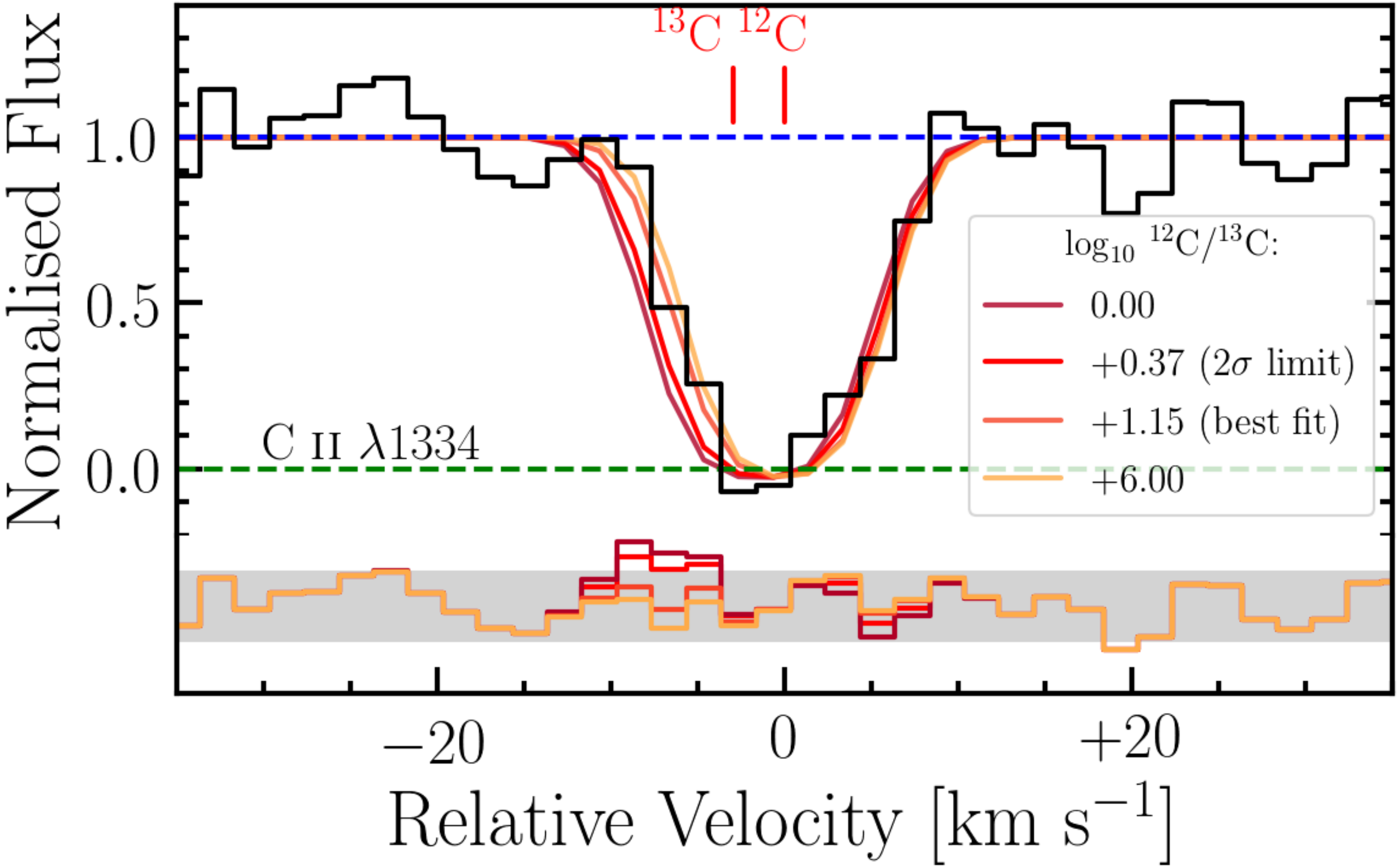
$\log_{10}{}^{12}C/{}^{13}C = 1.15$

Welsh et al. 2020

We performed a suite of Monte Carlo simulations to infer the ${}^{12}C/{}^{13}C$ isotope ratio distribution, given the data.

# A Lack of $^{13}$C

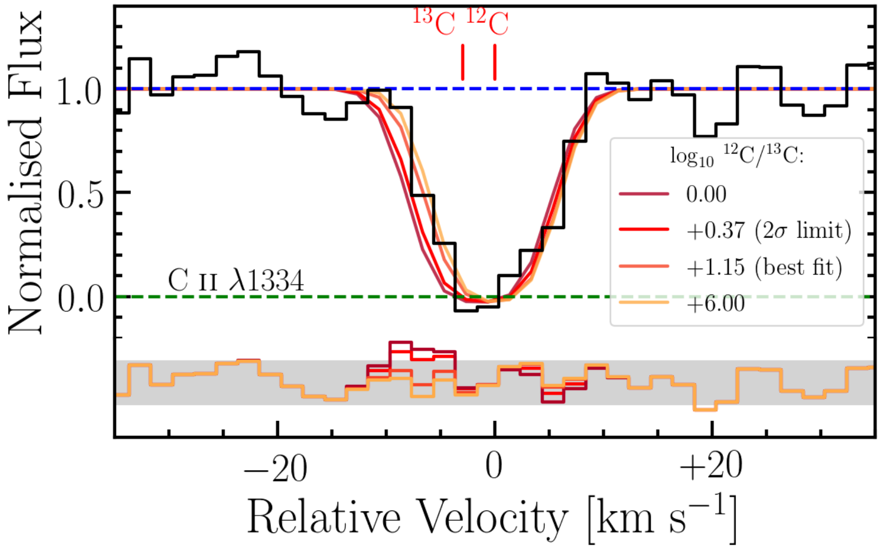
Welsh et al. 2020



# Overall Result

- $\log_{10}(^{12}C/^{13}C) > 0.37$ (2σ)
- $^{12}C/^{13}C > 2.3$ (2σ)
- We can rule out the presence of large amounts of $^{13}C$ in this DLA,
- However we cannot empirically rule out enrichment from low-mass Population III stars yet - more data are forthcoming!!

Welsh et al. 2020



# Stochastic Enrichment Model

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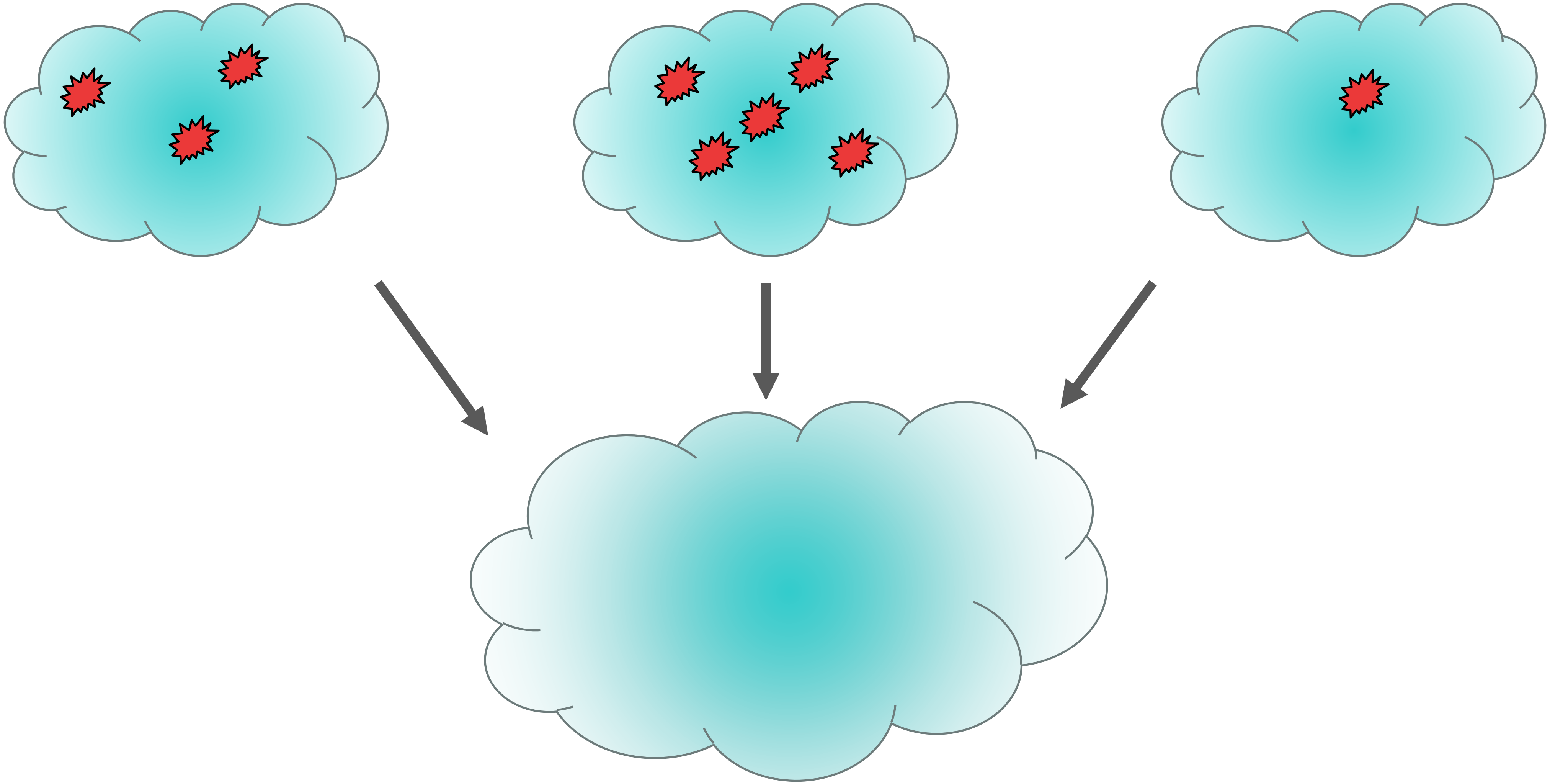

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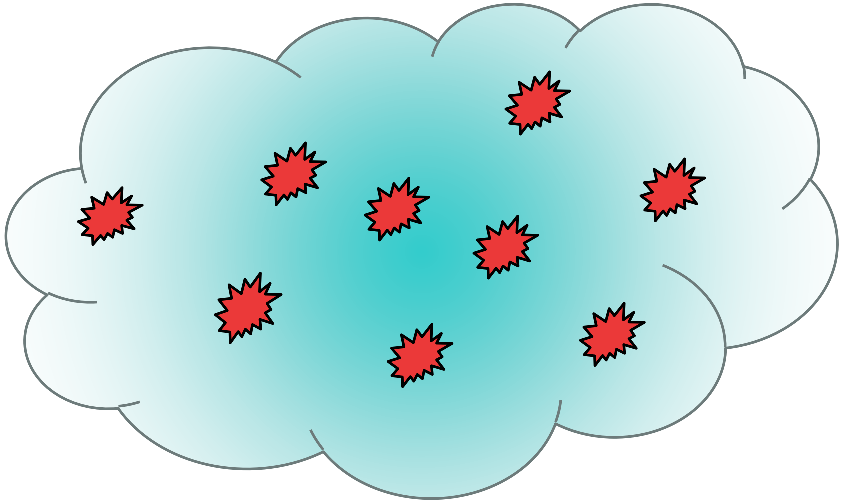

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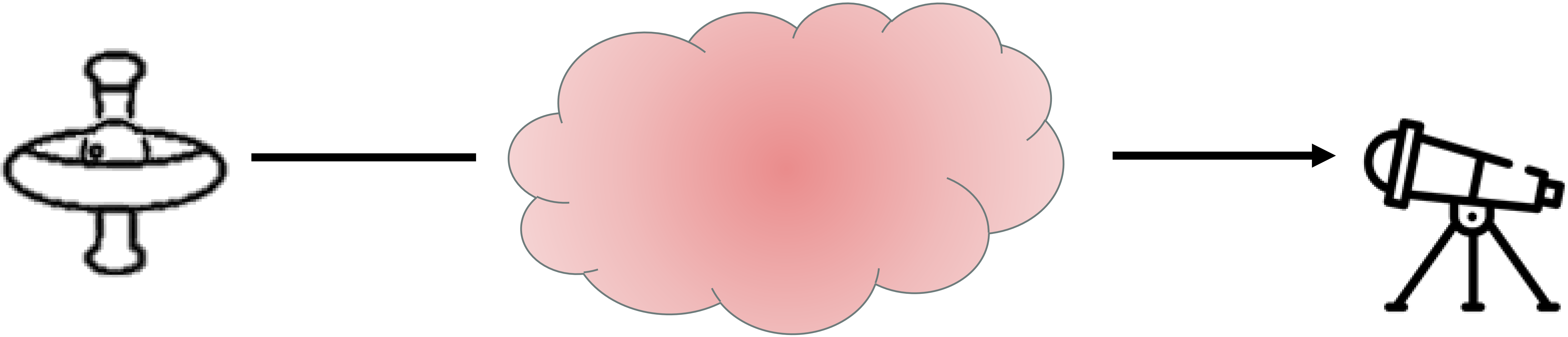


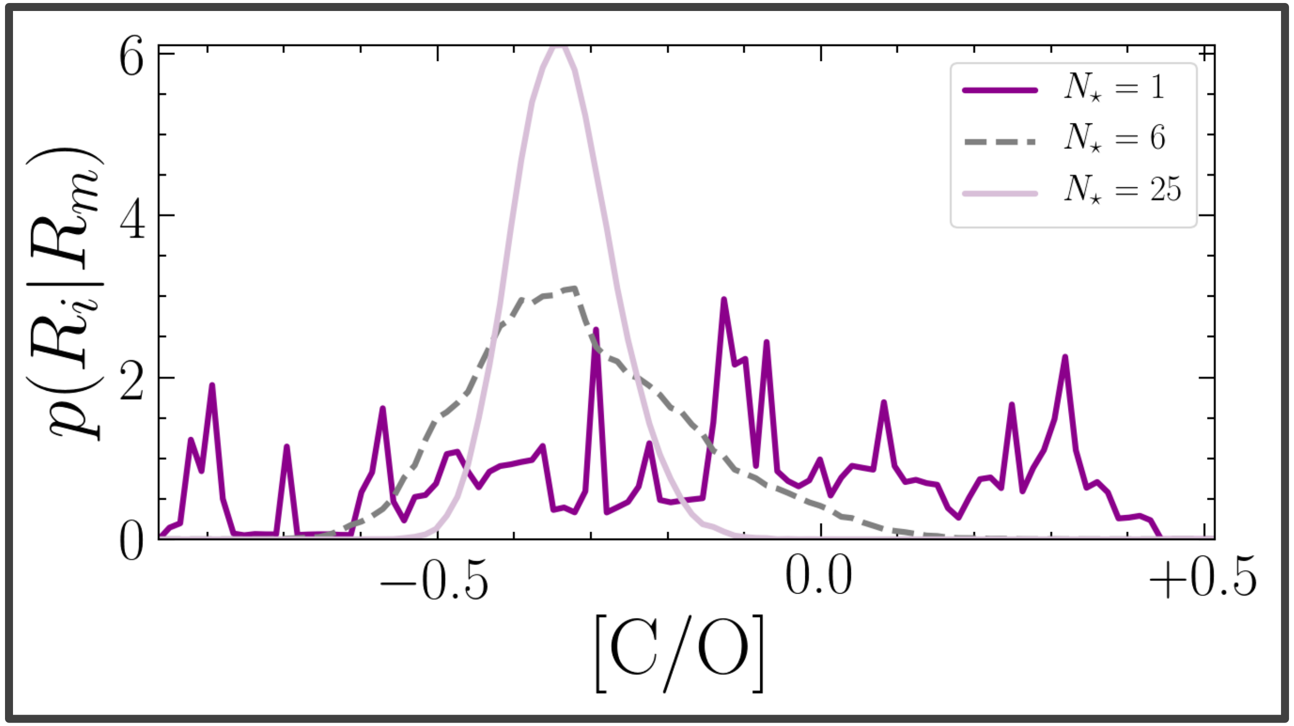
# Stochastic Enrichment Model

$$N_{\star} = \int_{M_{min}}^{M_{max}} kM^{-\alpha}dM$$

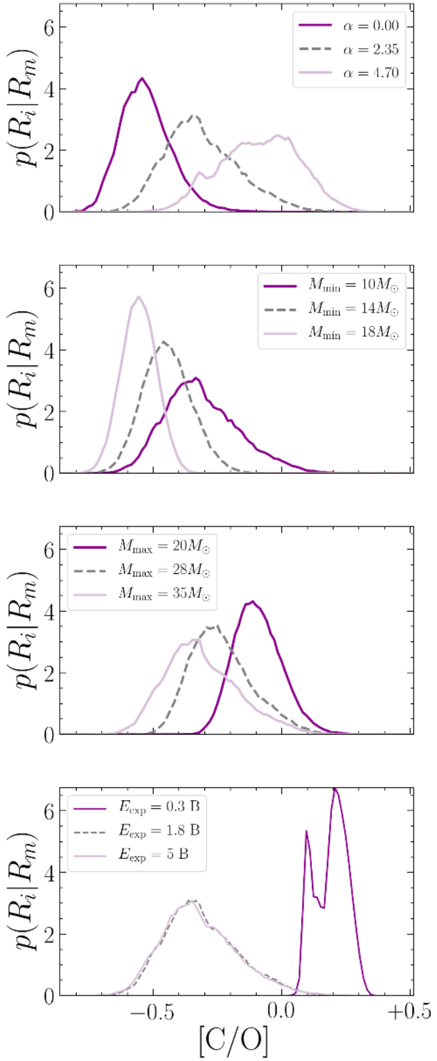
- $N_{\star}$ – number of stars which have contributed to a DLAs enrichment
- $M_{min}$ – minimum mass of enriching stars
- $M_{max}$ – maximum mass of enriching stars
- $\alpha$ – power law mass distribution (Salpeter = 2.35)
- $E_{exp}$ – the energy of supernova explosion at infinity

# Stochastic Enrichment Model

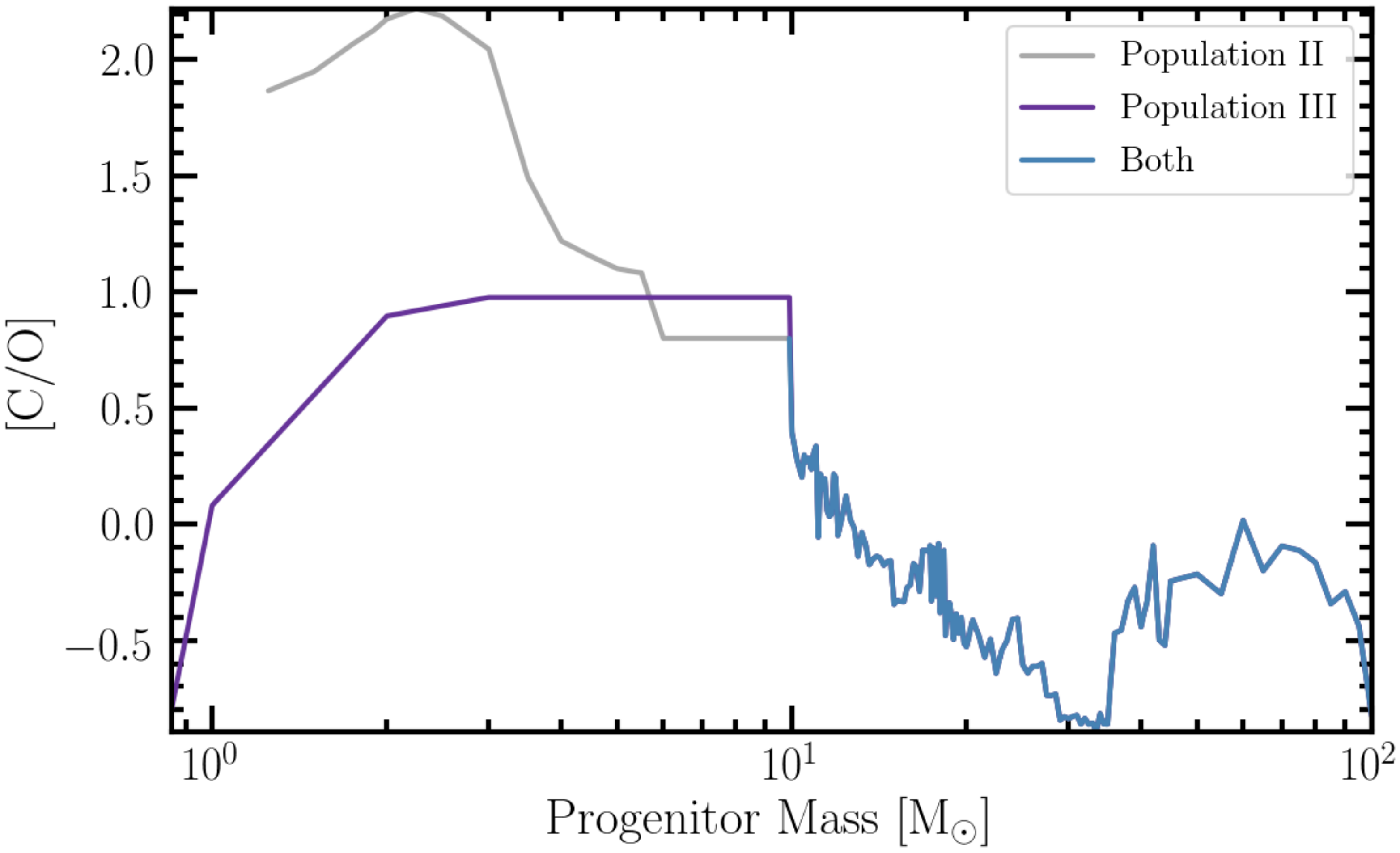
- Metal-free stars form either individually or in small multiples,
- Underlying IMF is stochastically sampled



Welsh et al. (2019)



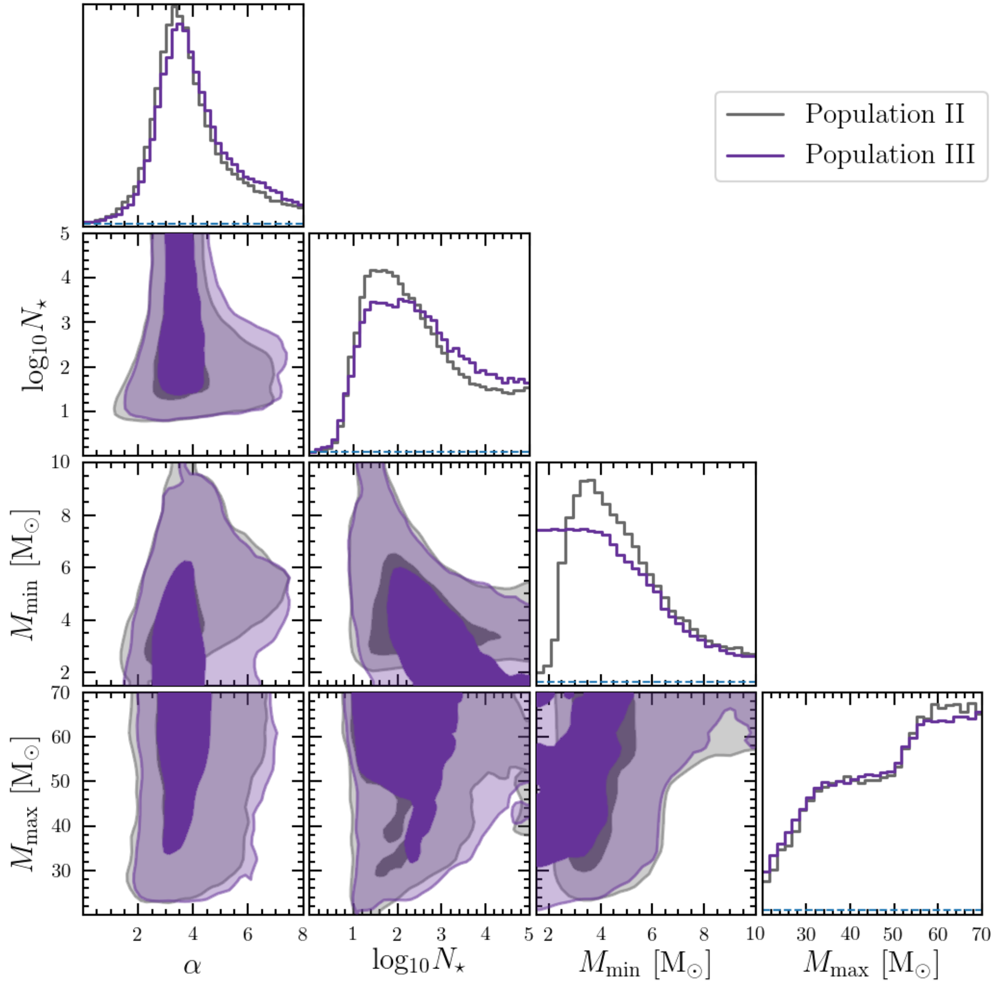
# Population III vs Population II [C/O]



# Likelihood Analysis

$$N_\star = \int_{M_{min}}^{M_{max}} k M^{-\alpha} dM$$

Welsh et al. 2020



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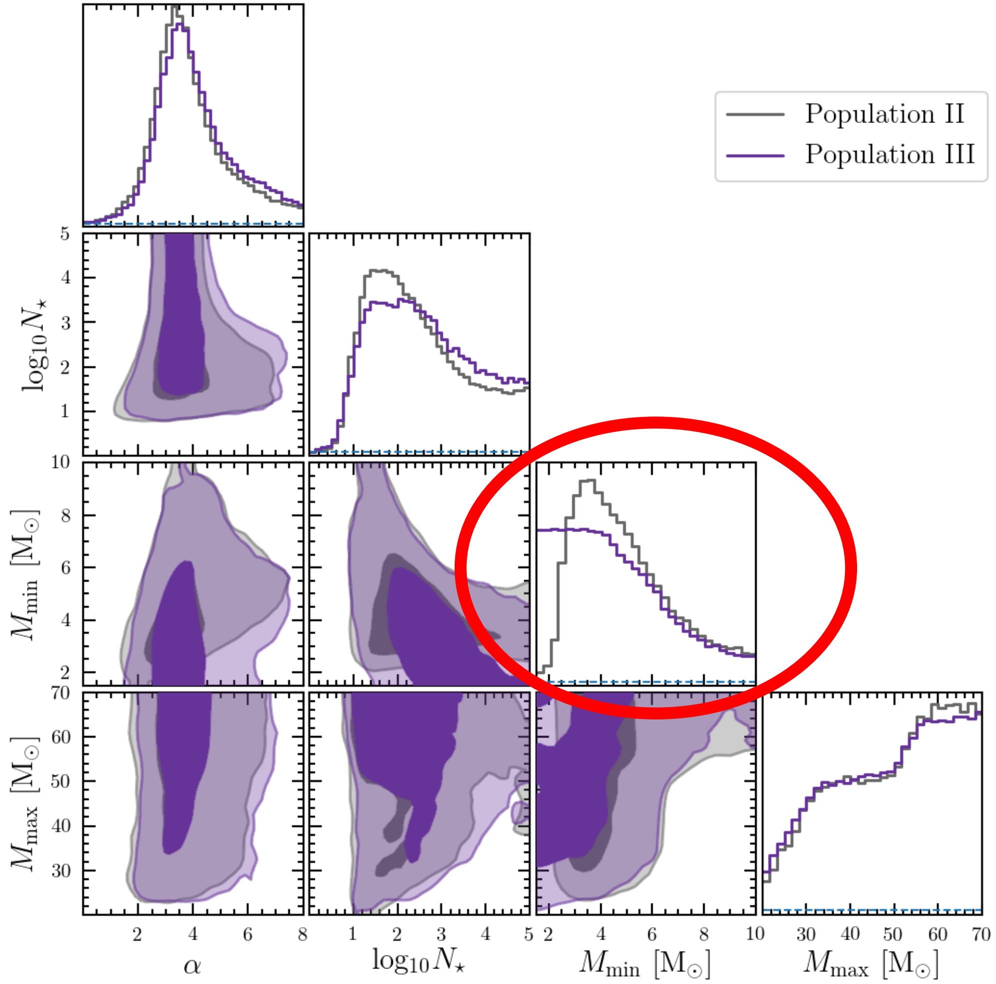

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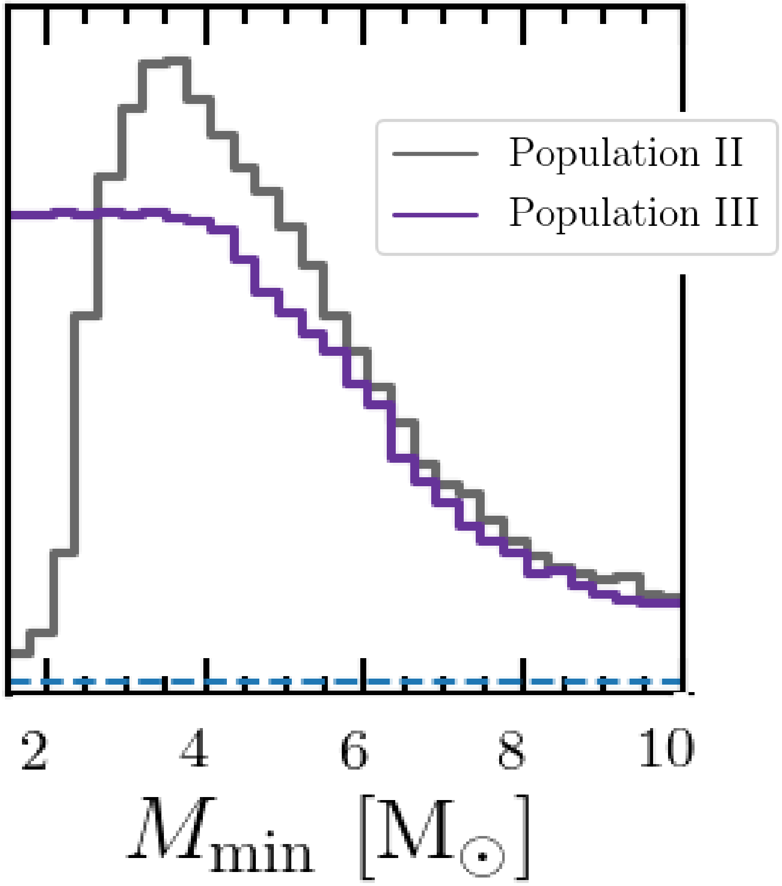
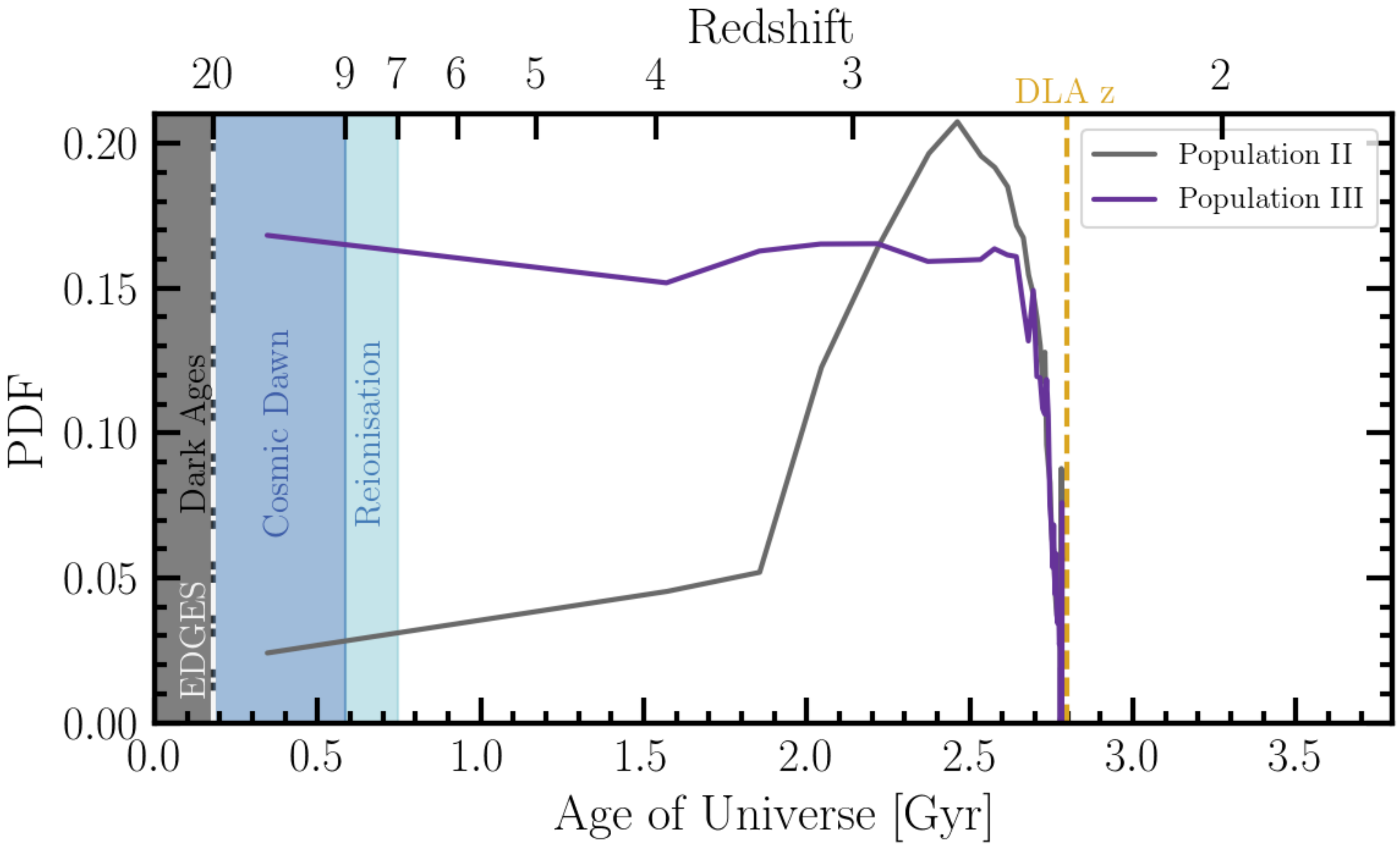


# Enrichment Timescale

Welsh et al. 2020



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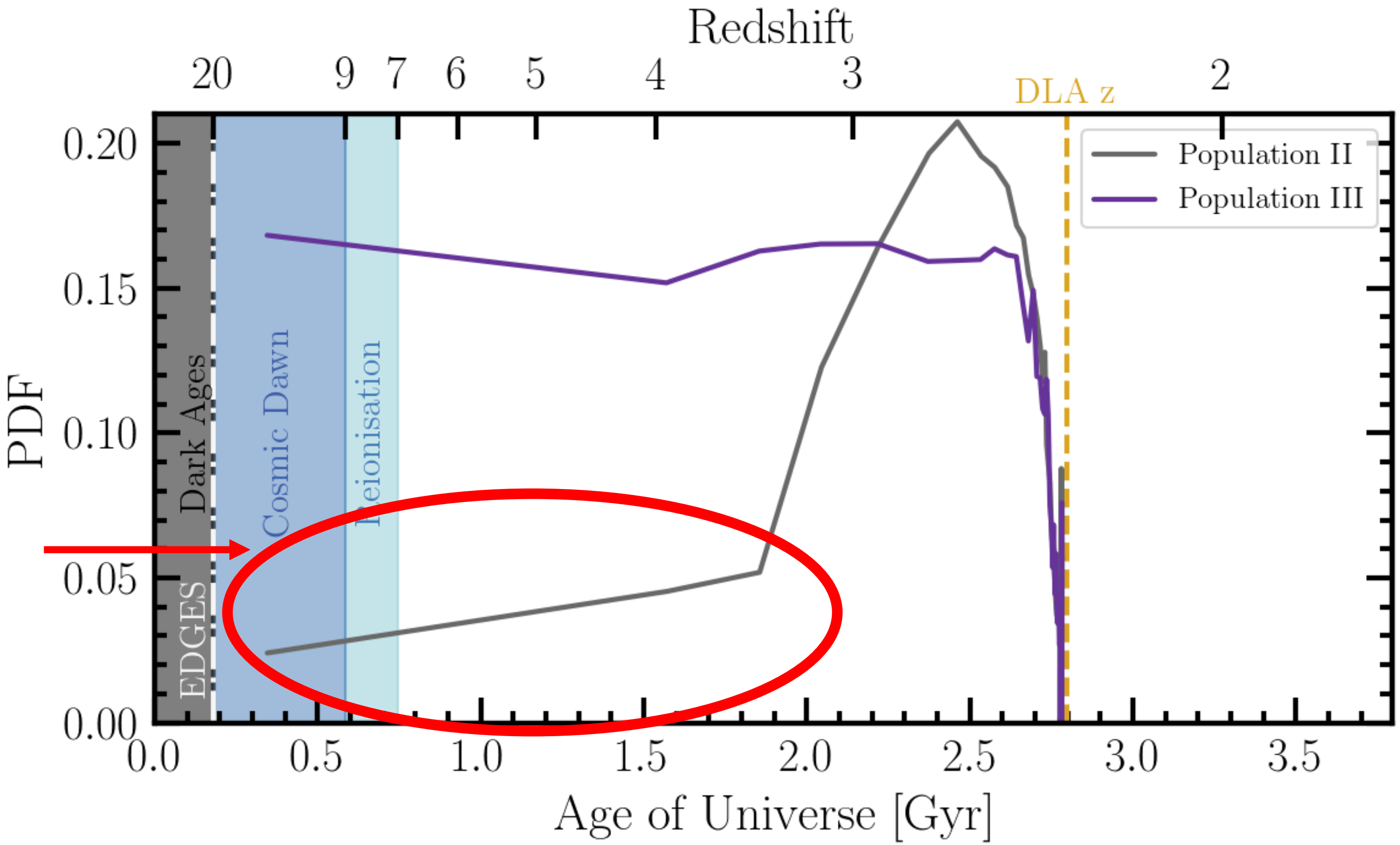
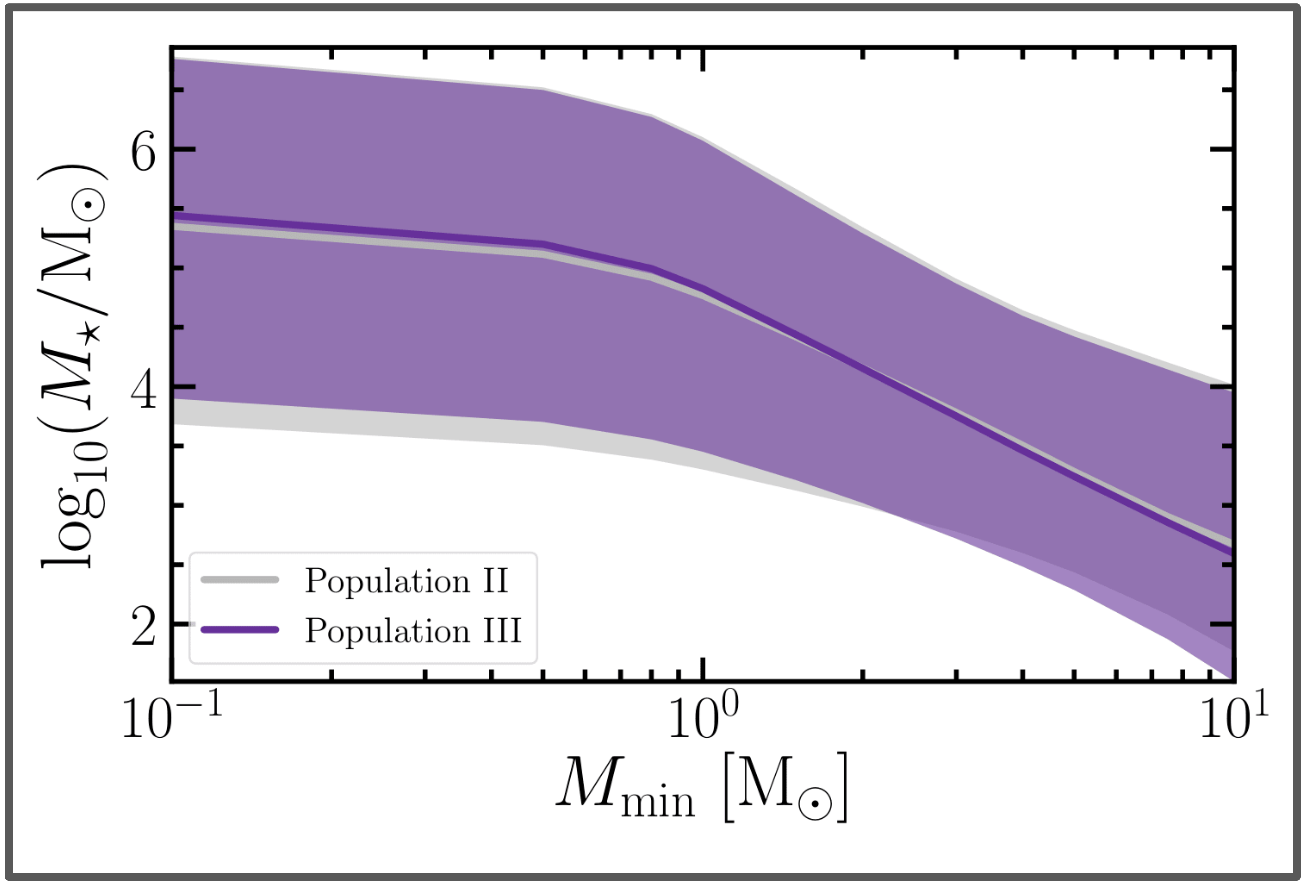


Following the epoch of reionisation there appears to be a lack of star formation for > 1 Gyr.

# Physical Properties of DLA

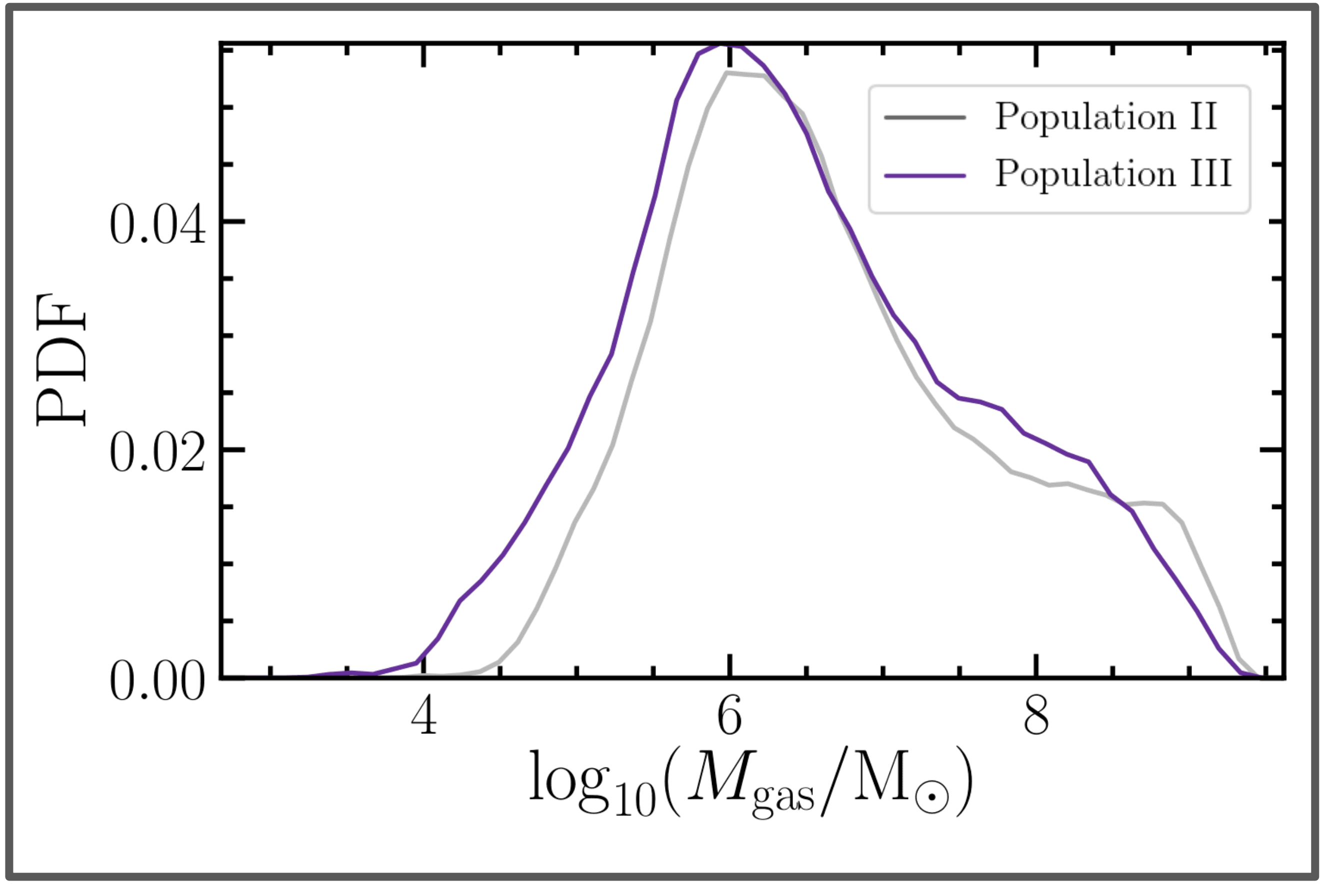
$$M_\star = \int_{M_{min}}^{M_{max}} \xi(M) M dM$$



- Know the mass distribution of massive stars from enrichment model,
- Assume this relationship holds for lower mass stars (> 1 $\mathrm{M}_\odot$) and adopt a log-normal IMF below 1 $\mathrm{M}_\odot$ (Chabrier 2003),
- Calculate the total stellar mass expected within this DLA as a function of the minimum mass with which stars can form.

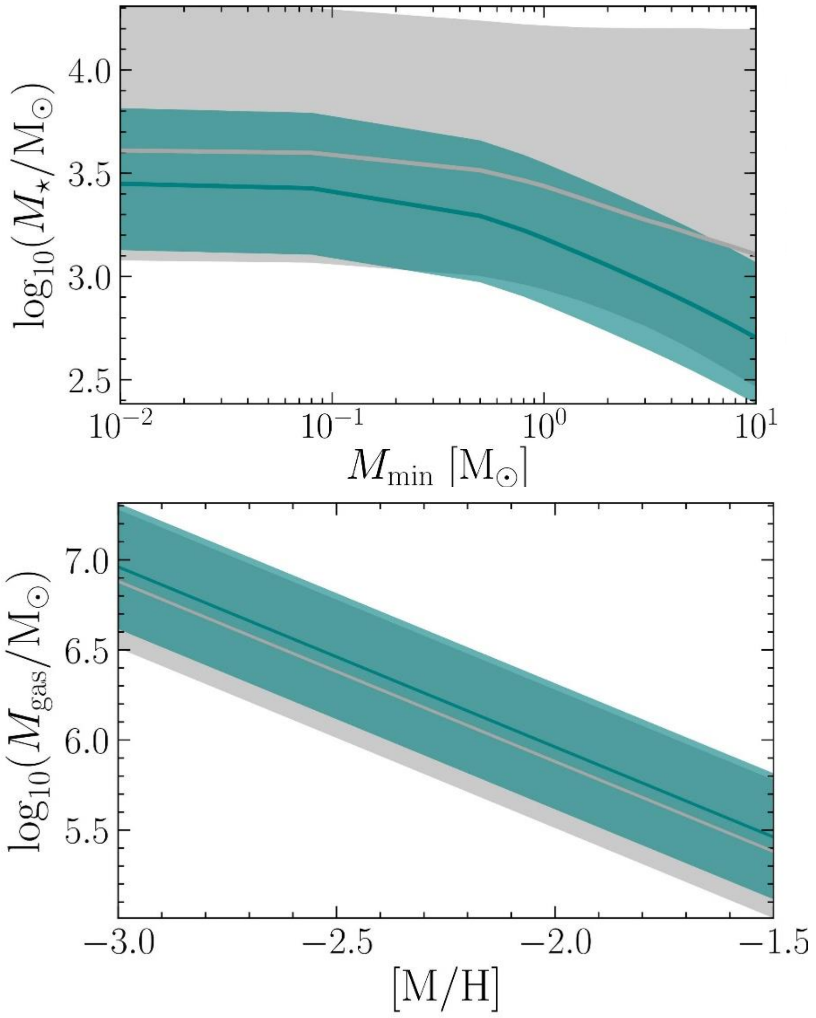
# Physical Properties of DLA

- Know total mass of metals in this system from enrichment model,
- Assume 100% retention of these metals,
- This puts an **upper** limit on the gas mass,
- Calculate the amount of pristine gas necessary to produce observed [O/H].



# Comparison with DLA Population

- Broadly consistent with that found for typical metal-poor DLA.
- What can these properties tell us about the descendants of metal-poor DLAs?
  - Comparable stellar content to that of the faint Milky Way satellite population (Martin et al. 2008; McConnachie 2012). These typically span a mass range of $\sim (10^2 - 10^5)\ M_\odot$
  - Ultra-faint dwarf galaxies still expected to contain gas at redshift ~3 (Wheeler et al. 2018).



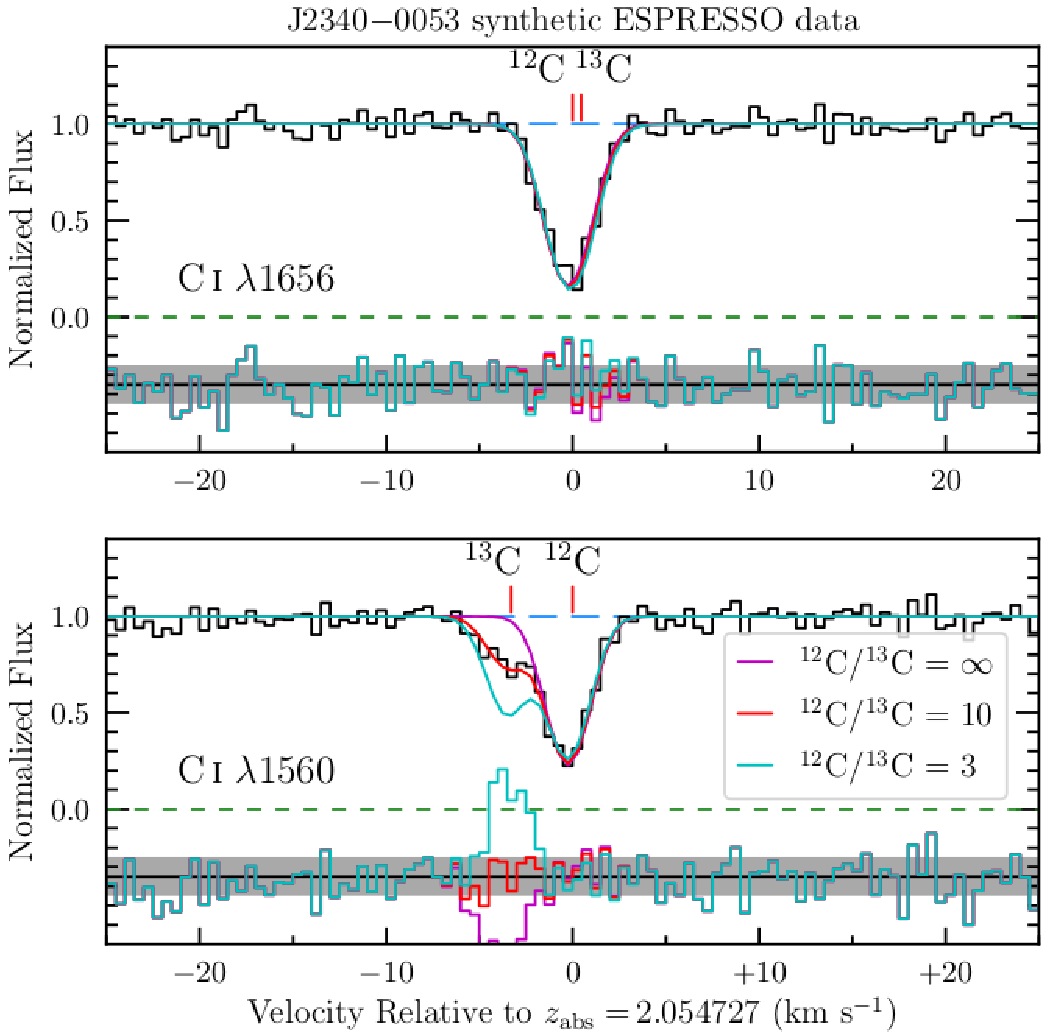
Welsh et al. 2019

# Conclusions

- Carbon isotope ratio is an informative probe of early stellar populations,
- We have recovered the first bound on this ratio in a near-pristine system using ESPRESSO and can confidently rule out the strong presence of $^{13}$C,
- To better investigate enrichment of the DLA towards J0035-0918 we need higher S/N data (forthcoming),
- Current enrichment model suggests that this DLA may have experienced a hiatus in star formation post-reionisation.

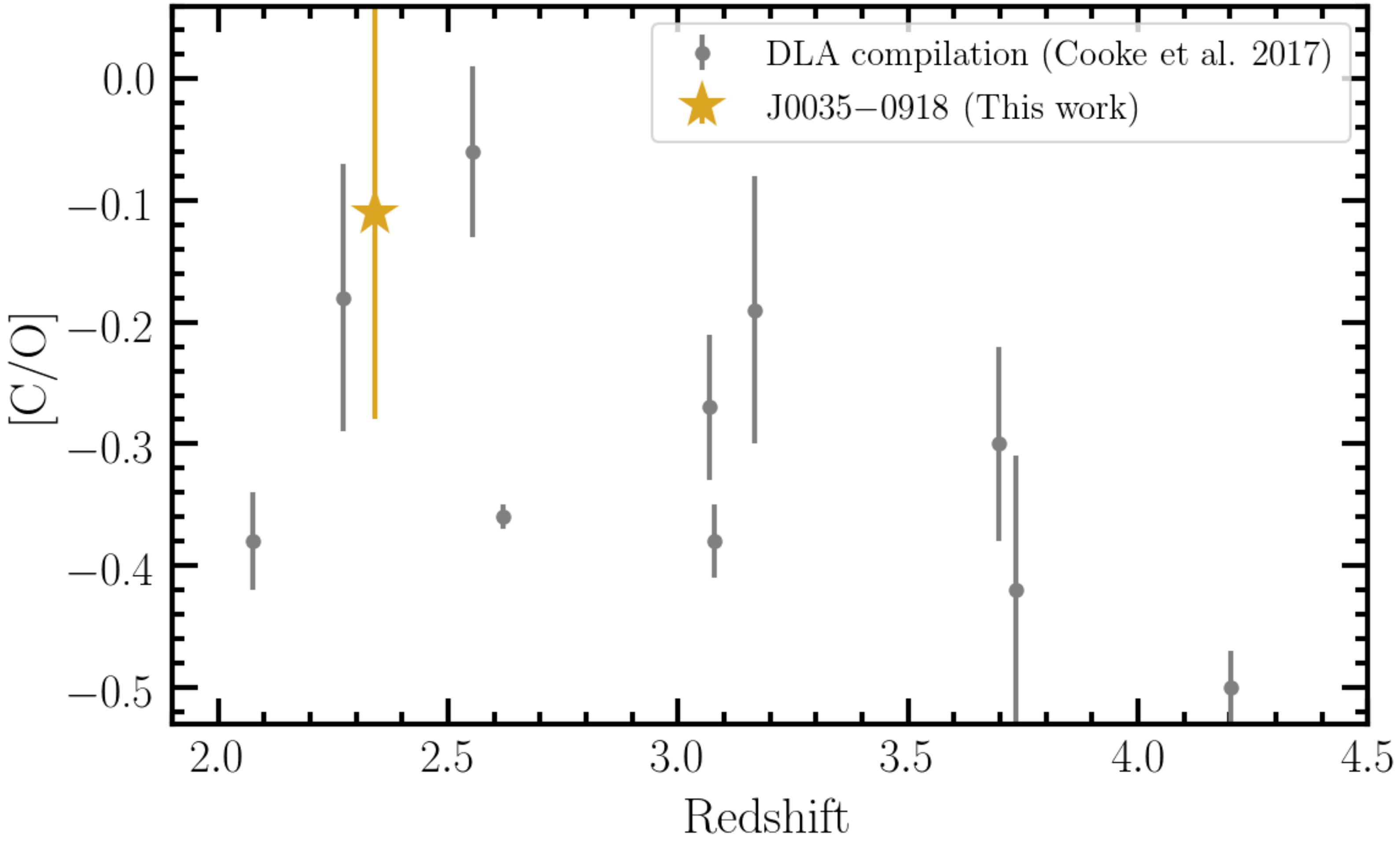
# Future

# Metallicity Evolution of 12C/13C



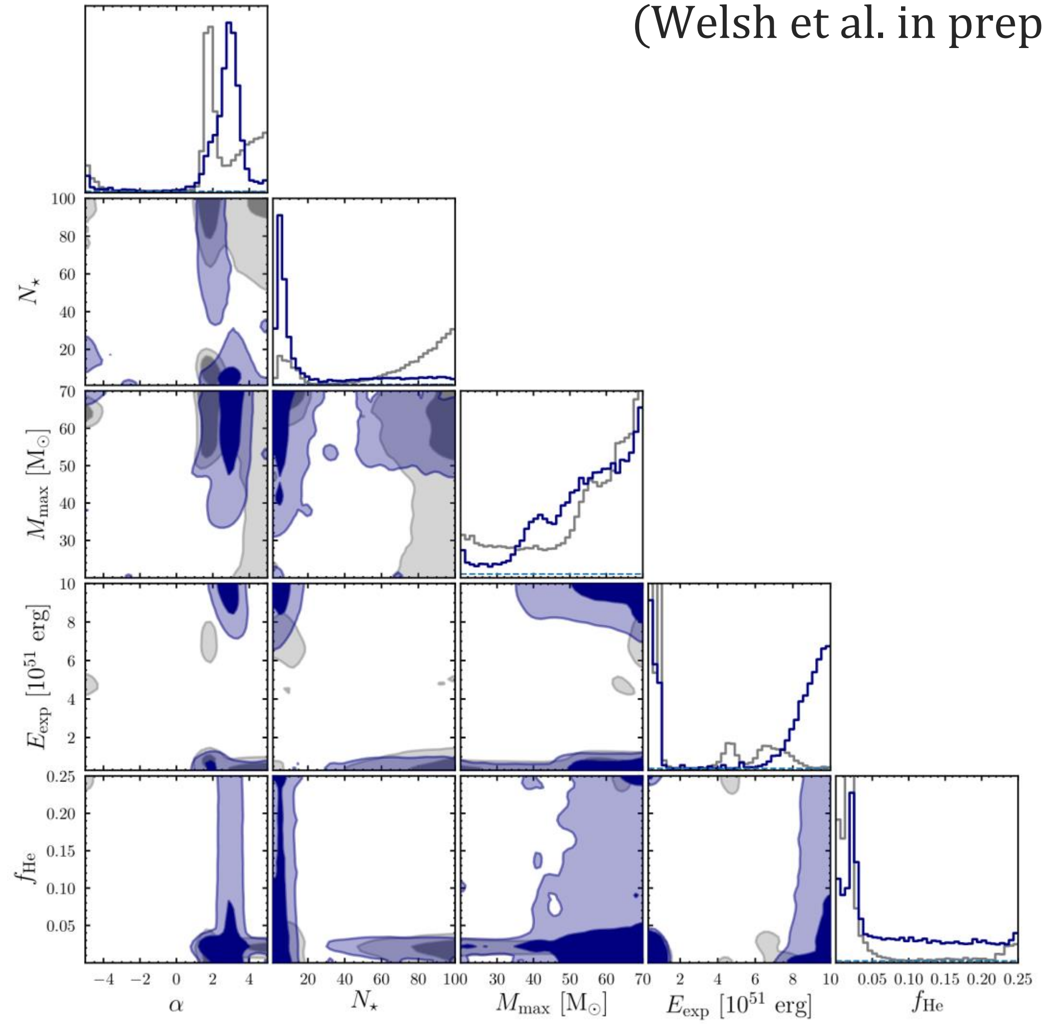
# Evolution with Redshift?

Welsh et al. 2020



# Enrichment of DLAs vs Population II stars

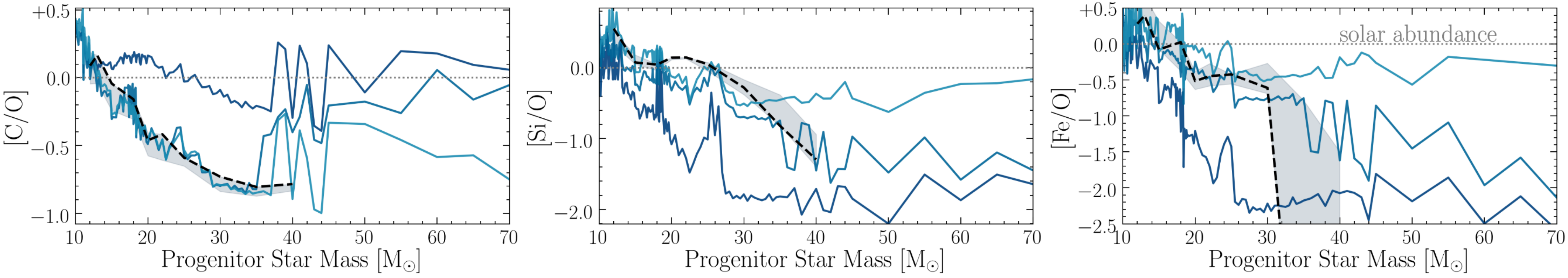
- Enrichment model is most powerful when looking at the distribution of abundances across a sample of objects,
- $N_{\star} < 72$ ($2\sigma$) for metal-poor DLAs (Welsh et al. 2019)
- $N_{\star} < 20$ ($2\sigma$) for metal-poor halo stars (Welsh et al. in prep)
- Caution: There are signs of tension between the observed stellar abundances and the simulated yields. The community needs a new set of (empirical/theoretical) yields with uncertainties.
- Potential to estimate Population III multiplicity and the number of minihalos that enrich the first surviving structures?



(Welsh et al. in prep.)

# Extra

# Yields



[C/O]
+0.5
0.0
−0.5
−1.0
[Si/O]
0.0
−1.0
−2.0
[Fe/O]
+0.5
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
solar abundance
10
20
30
40
50
60
70
Progenitor Star Mass [$M_\odot$]
Progenitor Star Mass [$M_\odot$]
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